DYNAMIC INCREMENT FACTOR IN MODULAR EXPANSION JOINTS OF BRIDGES UNDER HEAVY TRAFFIC LOADING

Ir. J. Maljaars	TNO Building and Construction Research, The Netherlands, e-mail
	j.maljaars@bouw.tno.nl, tel +31-15-2763464
Dr. Ir. P.H. Waarts	TNO Building and Construction Research, The Netherlands
Ir. J.S. Leenderts	Rijkswaterstaat, Ministry of transport, The Netherlands
Ir. Ing. R.B.J. Hoogvelt	TNO Automotive, The Netherlands

ABSTRACT

In order to obtain a better insight in why expansion joints fail, dynamic loads on the road near expansion joints in bridges and dynamic responses in the construction of modular expansion joints are measured and evaluated. For this purpose, a test vehicle has passed these expansion joints at various velocities. Both dynamic load of the vehicle and strains in the expansion joints were measured.

INTRODUCTION

Modular expansion joints are applied in many recently built bridges. These expansion joints form the connection between abutment and bridge, see figure 1. In this figure, an overview is given of the main construction parts establishing a modular expansion joint. The steel lamellas (center beams) transfer the traffic load to the cross beams, which are steel beams mounted in the bridge and in the abutment.

A commonly used design method for modular expansion joints in bridges is based on the calculation of stresses under quasi static loading. These stresses are multiplied by a dynamic amplification factor, which takes into account the roughness of the pavement near the expansion joint, and by a dynamic amplification factor, which takes into account the interaction between the time history loading and the dynamic response of the expansion joint, for which damping and eigen frequency of the expansion joint are important. In this paper, the first factor is referred to as dynamic amplification factor for loading, the second as dynamic amplification factor for interaction.

For current practice, Eurocode 1 part 3 (1991) prescribes a magnitude of 1.3 for the dynamic amplification factor for load. The dynamic amplification for interaction should be determined using equations prescribed in the Eurocode. Most manufacturers of expansion joints make such a design of the joint that the dynamic amplification factor is approximately 1. The total dynamic amplification is thus $1 \times 1.3 = 1.3$ for most designs.

In many bridges in The Netherlands, cross beams of modular expansion joints collapse long before the calculated life time, see figure 2. This is possibly caused by a dynamic increment in real bridges that exceeds the assumed magnitude in the design. Therefore, dynamic amplification factors were measured and analyzed with measurements for two bridges in The Netherlands, the bridge in motorway xx over xx near Zaltbommel: the "Martinus Nijhoffbrug" and the bridge in motorway xx over xx near Grubbenvorst: the "Noorderbrug". For these bridges, a dynamic amplification (load x interaction) of 1.4 is used in the design. This paper describes the measurements and analyses and the resulting dynamic responses.

PROCEDURE

An instrumented vehicle with two axles, weighing approximately 18 tons, crossed the expansion joints, see figure 4. Accelerometers were attached to the axles and chassis of this vehicle in order to determine the dynamic wheel load through a mass-spring-damper model. The vehicle model consists of two unsprung elements (front and rear axle) and two sprung chassis parts (front and rear) connected with a rotational joint to allow chassis roll. The model parameters are listed in table I. The input for the model are the eight measured accelerometer signals. The

output are the four wheel loads. The lateral position of the test vehicle corresponded to the lateral position of passages of normal traffic. A variation in lateral position of approximately 100 mm occurred for low velocities. For the measurements, strain gauges were attached on the under-surface of the cross beams of the expansion joint, see figure 3.

Measurements took place at a velocity of 5 km/h to determine the static response, and at a velocity of 50, 70 and 85 km/h to determine the dynamic response at various velocities. All measurements were repeated three times. During the measurements, the bridges were closed for other traffic.

The dynamic amplification factors for an expansion joint is determined in two steps: first, strains in the expansion joints are measured under a static loading. Strains divided by static loading result in the static transfer. Second, strains are measured under dynamic loading. The dynamic transfer is calculated as the dynamic strains divided by dynamic loading. The dynamic amplification factor for interaction is determined as dynamic transfer divided by static transfer, The dynamic amplification factor for loading is determined as the dynamic peak load divided by the static load.

DYNAMIC LOADING

Figure 5 shows accelerations measured at a velocity of 70 km/h for the "Noorderbrug". The upper picture shows accelerations at the axles while the lower picture shows accelerations at the chassis. The dynamic load is calculated from these accelerations by using a model of a two-mass-spring system per quarter of the vehicle, see [1]. The dynamic loads at the point where the vehicle crosses the expansion joint for the three measurements are shown in figure 6. As for this velocity, the repeated measurements for all velocities showed an extremely good similarity.

The dynamic amplification factor for loading is defined as the maximum dynamic load effect divided by the static load effect. The dynamic amplification factors for loading for various velocities for the vehicle used are shown in table II. Dynamic amplification factors for the bridge "Martinus Nijhoffbrug" are larger than for the bridge "Noorderbrug". The unevenness and roughness of the pavement near the expansion joint have significant influence on this dynamic amplification factor.

For calculation of the dynamic amplification factor for interaction, the load should be determined at the moment at which a strain gauge signal is maximal. While a small difference in time exists between the maximum signals for different strain gauges, the load differs for all strain gauges. Figure 7 shows the load for a measurement with velocity 70 km/h for the bridge "Noorderbrug". Dots indicate loads at the moment that a strain gauge signal was maximal.

The loads at the moment that the signal of strain gauge 2 is maximal are given in figure 8. It is shown that the three different measurements with the same velocity result in an almost equal load.

MEASURED STRAINS

Figure 9 gives an example of the strains measured at the heaviest loaded crossbeam of the bridge "Martinus Nijhoffbrug". The top picture shows results at a velocity of 5 km/h, the middle picture at a velocity of 85 km/h. For every measurement, the maximum strain and the range in strain (difference between maximum and minimum strain) are determined. Maximum strains for all measurements in the heaviest loaded crossbeam are shown in figure 10. Strains measured in cross beams 1 to 8 (numbers are referred to figure 2) are of the same magnitude, strains measured in cross beams 9 to 12 are a factor 5 to 10 lower. Figure 10 shows that the three different measurements with the same velocity result in an almost equal strain. In this figure, strains decrease for increasing velocity. However, this was not found for all cross beams.

At the bridge "Noorderbrug", strains vary slightly for the different measurements at low velocities. This is caused by a small change in lateral position of the vehicle, due to which some cross beams are loaded slightly heavier and others slightly lighter; the average strains measured at all cross beams show no significant difference between the measurements. The eigenfrequencies and the damping of the crossbeams are determined using the strain gauge signal, see the bottom picture in figure 9. The eigenfrequency measured at the bridge "Martinus Nijhoffbrug" was f = 139 Hz. The damping ratio is defined as the ratio between actual damping and critical damping. This damping ratio is $\phi = 5.0$ % for the bridge "Martinus Nijhoffbrug". For the bridge "Noorderbrug", eigenfrequency and damping ratio are f = 132 Hz and $\phi = 2.3$ %, respectively. Measured damping ratios are much lower than used in the design calculation for these expansion joints ($\phi = 10$ %), which means that much more load cycles with low load occur than assumed in the design. The lower damping ratios are lower than expected, probably because the damping decreases during lifetime.

INTERACTION BETWEEN LOADING AND DYNAMIC RESPONSE OF JOINT

The dynamic amplification factor for interaction indicates the change in stresses at a change in velocity when loading remains constant. It is calculated as the ratio between dynamic transfer (strains divided by load under dynamic loading) and static transfer (strains divided by load under static loading). The dynamic amplification factors for interaction at various velocities presented here are the average of the three measurements.

Dynamic amplification factors for interaction for loading by the front axle are shown in figure 11 for the bridge "Martinus Nijhoffbrug". Maximum strains measured in cross beams 9 to 12 have a magnitude of 10 times lower than the heaviest loaded cross beam. Although the dynamic amplification factors for interaction for these strain gauges are relatively high, the resulting dynamic strains remain low. Therefore, the dynamic amplification factors for interaction for these cross beams are of less significance and are not shown in figure 11. The weighing average of the dynamic amplification factors for interaction is defined as the sum of the products of dynamic increment factors and strains for all strain gauges divided by the sum of the strains of all strain gauges. The weighing averages for maximum strains and range in strains at loading by the front or the rear axles for all velocities are listed in table III.

The maximum dynamic amplification factor for interaction for strains in cross beam 5 was 1.96 for range in strains, which occurred for loading by the front axle at a velocity of 85 km/h. This means that the maximum strain for a dynamic load is nearly twice the strain for a static load, when the load magnitude on the expansion joint remains equal.

Dynamic amplification factors for range in strains at loading by the front axle are shown in figure 12 for the bridge "Noorderbrug". Maximum strains measured in cross beams 5 and 6 have a magnitude of 3 times lower than the heaviest loaded cross beam. The weighing averages for maximum strains and range in strains at loading by the front or the rear axles for all velocities are listed in table IV.

The maximum dynamic amplification factor for interaction for strains in cross beam 3 was 1.57 for range in strains for loading by the front axle at a velocity of 85 km/h.

FATIGUE LIFES FOR ORIGINAL DESIGN AND USING NEW PARAMETERS

The highest measured amplification factors for loading and for interaction were 1.7 and 1.9 respectively. However the moment that the strain gauge gave a maximum signal did not correspond to the moment at which the peak in the load occurred. The product of the actual dynamic load times the amplification factor for interaction was maximal 1.57 but for most cross beams this product was approximately 1.0. In the design, 1.4 was assumed for the product of the two amplification factors. The measured damping ratio was 2.3% and 5%, while 10% was assumed in the design.

Fatigue calculations have been carried out with different values for damping and products of the dynamic amplification factors. In these calculations, the load cycles of the cross-beams were determined for loading by 1000 axles. Equivalent static axle loadings were calculated using the magnitude of the load cycles and the gradient of the logarithmic s-N curve of 3. Results are shown in table V. The equivalent axle loadings, fatigue damage and fatigue lifetime for calculation with a damping and a dynamic amplification factor used in the original design is used as a base. It is shown that lower damping and higher dynamic amplification factor leads to a much lower calculated life time.

CONCLUSIONS AND RECOMMENDATIONS

With the measurements carried out, a good insight has been obtained in dynamic impact loads on the road near expansion joints in bridges and dynamic responses in the construction of modular expansion joints.

All measurements at a specific velocity were repeated three times. Both strain gauge signals and dynamic loads showed extremely good similarity between these three measurements, indicating that the followed measuring procedure is a reliable method for obtaining information on dynamic amplification factors for traffic loading and dynamic amplification factors for interaction between time history loading and dynamic response of the cross beams in expansion joints. Dynamic amplification factors for loading and for interaction vary widely for different velocities and different cross beams. The highest measured dynamic amplification factors for loading and for interaction were 1.7 and 1.9, respectively. The highest difference in measured strains between static loading and dynamic loading was xx, while 1.4 was assumed in the design. The measured damping ratio were 2.3% and 1.5%, while 10% was assumed in the design.

The dynamic amplification factors for loading and for interaction and the damping play a large role in the fatigue life of the expansion joints. A higher occurring dynamic amplification factor (1.8 instead of 1.4) leads to higher amplitudes in the response functions and result in a calculated fatigue life that is half the originally determined fatigue life of the structure. A lower occurring damping ratio (2.5% instead of 10%) leads to more load cycles and a higher dynamic amplification factor for interaction and results in a calculated fatigue life that is 40% of the originally determined fatigue life of the structure. A combination of higher occurring dynamic amplification factor and lower damping leads to a calculated fatigue life that is 20% of the originally determined fatigue life of the structure.

The dynamic loading is a combination of axle load and dynamic effects. Different vehicles with different axle loads may cause other dynamic amplification factors. The realistic dynamic amplification factor is defined as the maximum probabilistic dynamic load divided by the maximum probabilistic static load. For the maximum probabilistic static load, reference is made to the paper [2]. It is recommended to carry out measurements with other vehicles to obtain a complete range of dynamic amplification factors for realistic traffic, with which it is possible to obtain a maximum probabilistic dynamic load.

The dynamic increment factor depends on the geometry of the expansion joint and on dynamic loading. It is recommended to carry out measurements on other bridges to obtain a complete range of appearing dynamic increment factors.

In designs, it is recommended to take into account the actual dynamic interaction between loading and response. A damping ratio of 10% is not appropriate for life time calculations, because the damping decreases during lifetime.

Although only based on these two measurements carried out, the assumed dynamic amplification factor for loading in Eurocode 3 of 1.3 seems to be too low.

REFERENCES

- J. Maljaars, P.H. Waarts, R.B.J. Hoogvelt, Metingen aan de voegovergangen bij de brug bij Zaltbommel en Grubbenvorst, TNO report 2002-CI-R1054, 2002.
- A.C.W.M. Vrouwenvelder, P.H. Waarts, Traffic loads on bridges, Structural Engineering International, IABSE, August 1993.

TABLES & FIGURES



Top view of the modular expansion joint



Figure 1 - Modular expansion joint in the bridge "Martinus Nijhoffbrug", The Netherlands



Figure 2 - Crack in the modular expansion joint of the "Martinus Nijhoffbrug", The Netherlands (view from under the expansion joint)



Figure 3 - Cross-section of the expansion joint construction



Figure 4 - Vehicle used for measurements

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Element	Parameter	Unit of measure	Value	
Chassis	Mass	kg	16700	_
	Pitch inertia	kgm ²	53718	
	Roll inertia front	kgm ²	1040	
	Roll inertia rear	kgm ²	1691	

	Distance CG to front axle	m	3.46
	Distance CG to rear axle	m	2.13
Front axle	Mass	kg	650
	Pitch inertia	kgm ²	540
	Track width	m	2.02
Rear axle	Mass	kg	1125
	Pitch inertia	kgm ²	634
	Track width	m	1.85



Figure 5 - Accelerations at the "Noorderbrug" at 70 km/h



Table II -	Dynamic	amplification	factors
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velocity	dynamic ampl factor "Martinus Nijhoff"	dynamic ampl factor "Noorderbrug"
50 km/h	1.5	1.1
70 km/h	1.6	1.2
85 km/h	1.7	1.4



Figure 7 - Loads at maximum strains at a velocity of 70 km/h, "Noorderbrug" Translation of text: snelheid - velocity



Figure 8 - Loads at maximum strains at strain gauge 2, "Noorderbrug"







Figure 9 - Strain measured at cross beam 7, "Martinus Nijhoffbrug"



Figure 10 - Maximum strains at various velocities, cross beam 7, "Martinus Nijhoffbrug"

Figure 11 - Dynamic increment factors for range in strains at the "Martinus Nijhoffbrug"

velocity (km/h)



Table III - Weighing average of dynamic increment factors, "Martinus Nijhoffbrug"



Figure 12 - Dynamic increment factors for range in strains at the "Noorderbrug"

	50 km/h	70 km/h	85 km/h
Maximum, front axle	0.93	0.92	1.02
Range, front axle	1.00	1.00	1.12
Maximum, rear axle	1.00	0.94	0.91
Range, rear axle	1.08	1.04	1.03

Table IV - Weighin	g average of d	ynamic increment	factors,	"Noorderbrug"
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Table V - Equivalent axle loads and fatigue life factor	s for variation in damping and dynamic amplification factors
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Damping	Dynamic amplification factors	Equivalent cycles	Equivalent damage	Fatigue life factor
Damping 10%	DAF = 1.8	2186	1.9	0.53
	DAF = 1.4	1145	1.0	1.0
	DAF = 1.0	631	0.6	1.7
Damping 2.5%	DAF = 1.8	5812	5.1	0.2
	DAF = 1.4	3005	2.6	0.4
	DAF = 1.0	948	0.8	1.3

