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Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **76 (1997)**

PDF erstellt am: **23.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-57465

Stress Reduction due to Surfacing on Orthotropic Steel Decks

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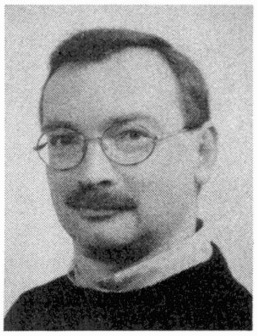

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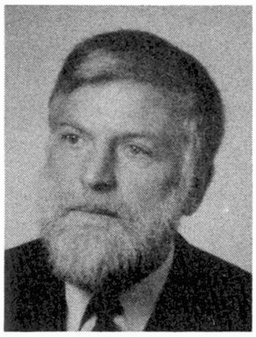


Summary

The composite action between the steel deck plate of orthotropic bridge decks and the surfacing is an important aspect for the performance, since the stiffness of the combined unit reduces the strains in the welded structure as well as in the surfacing, resulting in a longer fatigue life. Since the stiffness behaviour of the bituminous surfacing is strongly influenced by temperature, loading frequencies and the composition of the total surfacing, the stress reducing effect in the steel components cannot easily be described and included in design rules. Excluding this effect for the calculated design life of the orthotropic decks gives considerable underestimation. On the other hand there is a tendency for the surfacing to crack above the longitudinal welds between the troughs and the deck plate. This paper reviews the numerical and experimental analysis of the composite action. It further highlights site measurements on two existing bridges for studying the temperature effect.

1. Introduction

1.1 Orthotropic steel bridge decks

Modern steel bridge decks consist of a 10-14 mm thick deck plate stiffened by 6 mm closed longitudinal stiffeners spanning in the direction of the traffic flow between the transverse stiffeners. Usually the deck plate of fixed bridges is surfaced with a 50-70 mm thick surfacing of e.g. mastic asphalt. As shown in Fig. 1 the so called orthotropic deck is a flexible structure which is highly sensitive to the local bending action produced by the wheel loads of heavy commercial vehicles. During its lifetime, the bridge steel deck including the surfacing can be expected to suffer many millions of cycles by wheel loading, so that fatigue is an important design criterion.

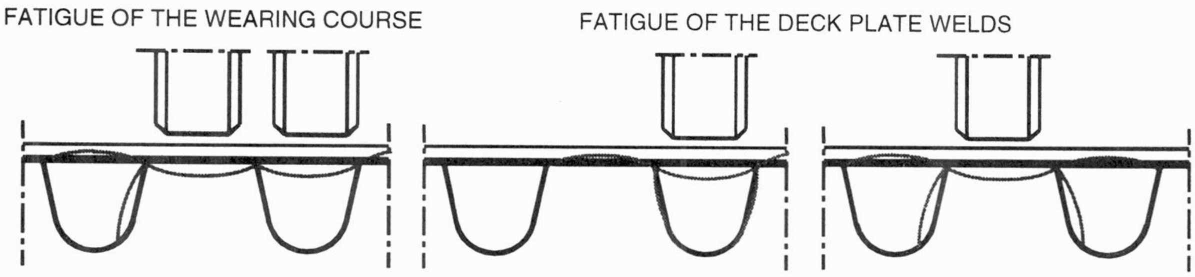


Fig. 1 Effects of local wheel loading on orthotropic steel bridge decks

1.2 Desirable properties and qualities of the surfacing

The surfacing on the bridge requires an acceptable flexibility to ensure a good fatigue performance and it is equally important that the surfacing possesses enough resistance against rutting of the wheel loads. Extensive deformations of the surfacing results in high and unacceptable dynamic effects in the steel deck. Further the steel deck has to be protected against corrosion by one of the layers in the surfacing. Nowadays porous wearing courses are very popular in The Netherlands [5, 7]. The reason for this is mainly, that they give comfort to the use of the road. They have a high skid resistance, they reduce the noise nuisance, prevent splash and spray water, while aquaplaning is in principle impossible.

1.3 Composite action between steel deck and surfacing

The composite action between the steel deck plate of orthotropic bridge decks and the surfacing is an important aspect of the performance, in particular because the stiffness of the combined unit reduces the strains in the welded structure as well as in the surfacing, which results in a longer fatgue life.

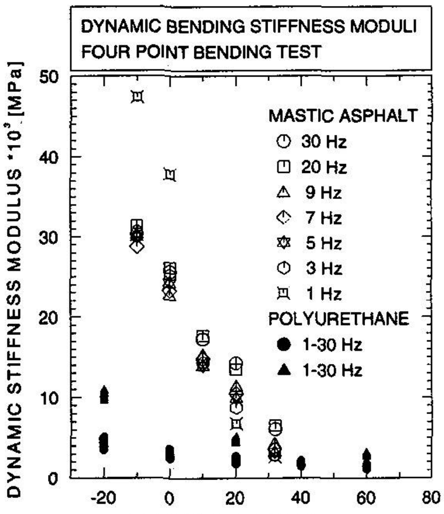


Fig. 2 Bending stiffness moduli

1.3.1 Dynamic bending stiffness moduli

Since the stiffness behaviour (Fig. 2) of the bituminous wearing course is strongly influenced by temperature, loading frequencies and composition of the total surfacing, the stress reducing effect in the steel components cannot easily be described and included in design rules.

Recently developed surfacing systems using polyurethane binders show dynamic stiffness moduli of a rather constant value, especially at temperatures above zero degrees. At low temperatures the values are considerably lower than the systems using bitumen binders.

1.3.2 Fatigue assessment of welded connections

A summary of fatigue lifes of several connections in orthotropic steel bridge decks for particular loads have been published by Gurney [4] and are partly shown in Table 1. All lives relate to a 2.3% probability of failure and a traffic flow of 800.000 lorries per annum. It can be seen that, for the unsurfaced deck, none of the details met the 120 years design life required by the Britsh Standard.

Joint (weld class-BS5400)	Unsurfaced deck	Surfaced deck
Stiffener to deck (F)	6.5	94
Longitudinal butt weld (F)	5.9	>120
Web of box to deck (D)	41	>120
Stiffener to crossbeam (G)	4.3	13
Crossbeam to deck (D)	94	>120
Transverse butt weld (F)	35	>120

***Table 1** Fatigue life of joints (years) by Gurney [4]*

1.3.3 Durability of the surfacing

There is a tendency for the surfacing to crack above the longitudinal welds between the troughs and the deck plate. To maximise the period between the costly and traffic-disruptive resurfacing operations less traffic susceptible systems have to be applied. Full scale tests carried out by Kolstein and all. [6] on several types of surfacing systems showed that an improved wearing course can only result in a longer life if the dynamic bending stiffness modulus is at least equal to that of the conventional systems and the fatigue strength of the wearing course is higher than the conventinal one.

2. Theoretical analysis of the composite action

The composite effect has been calculated by Kolstein [7] for different steel plate thicknesses (10-16 mm) and layer thicknesses (5-80 mm), various dynamic stiffness moduli (1.000-30.000 MPa) and the effect of the interlayer (flexible or stiff). The model used consists of a beam which is loaded by a constant moment which results in 70 MPa for a 12 mm steel plate without surfacing. The strains for a flexible and a stiff interface between the steel and the wearing course are shown in Fig. 3. for locations at the underside of a 12mm steel plate and the topside of the wearing course. The results for different thicknesses of the steel plate in combination with a 50mm surfacing are given in Fig. 4.

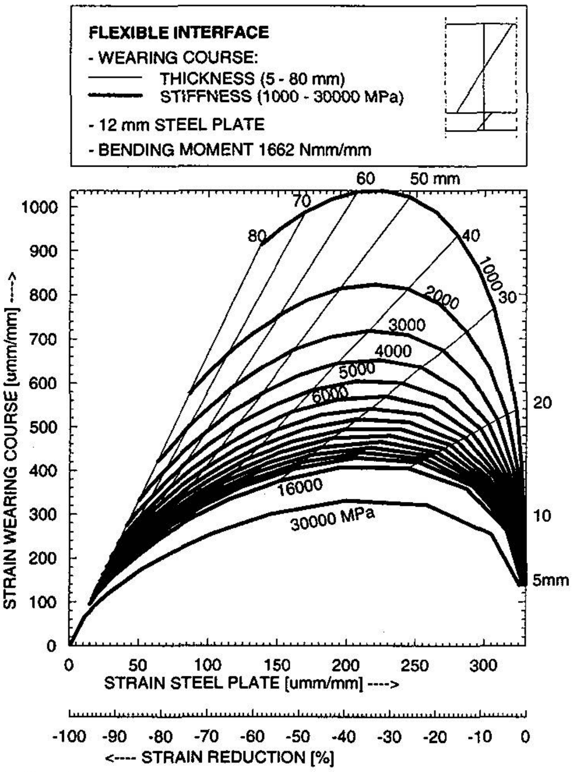


Fig. 3a Strains assuming a flexible interface.

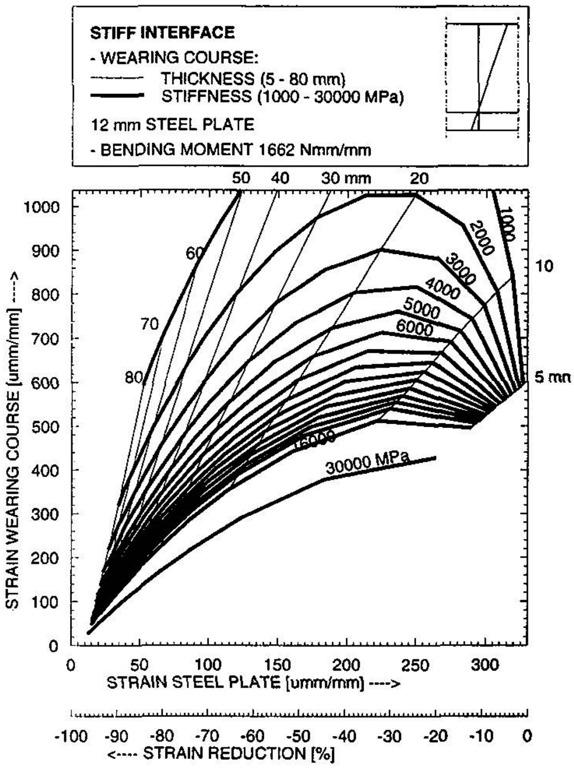


Fig. 3b Strains assuming a stiff interface.

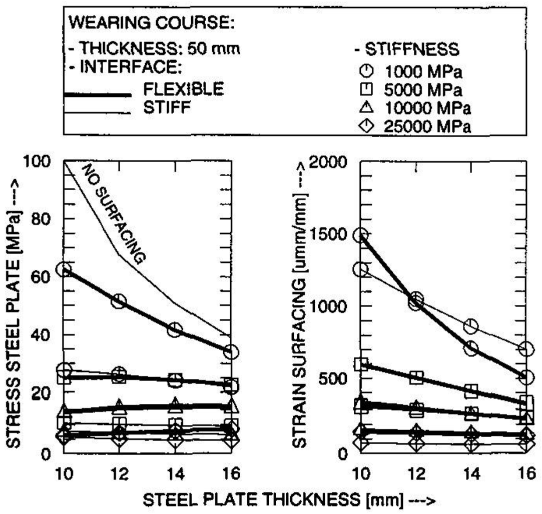


Fig. 4 Influence of steel plate thickness

As shown in Fig. 2 the dynamic stiffness moduli of the wearing couse at low temperatures is relative high (25000-30000 MPa) and at higher temperatures relative low (2000-5000 Mpa). From Fig 3 it can be seen e.g. that for a 50mm surfacing the strain reduction in the steel as well as in the surfacing at low temperatures is very high (±90%). At higer temperatures the strain reduction in the steel plate is still exceeds 40% and in the surfacing limited to about 20%. From Fig. 4 it can be concluded that the influence of the steel plate thickness is relatively small. The thickness and the stiffness of the wearing course as shown in Fig. 2 and 3 are much more important. Tests carried out by Kolstein [6] showed that for mastic asphalt systems the interlayer between the wearing course and the steel behaves stiff at temperatures below 20°C and relatively flexible above 20°C.

3. Laboratory tests with respect to the composite action

The effects of the surfacing on the stresses in the steel deck have been investigated by Smith et all. on a full scale section of a steel deck of Vee-stiffeners [9]. Static as well as dynamic loading arrangements in the surfaced and unsurfaced condition were carried out (see Fig. 5). Under dynamic loading, which refers to a pulse duration of 0.1sec, stress reduction of about 64-84% at 35°C have been found in a 12mm steel deck due to the composite effect of the 50mm asphalt surfacing (see Table 2). At 15°C and -5°C the stress reduction were about 84-98%.

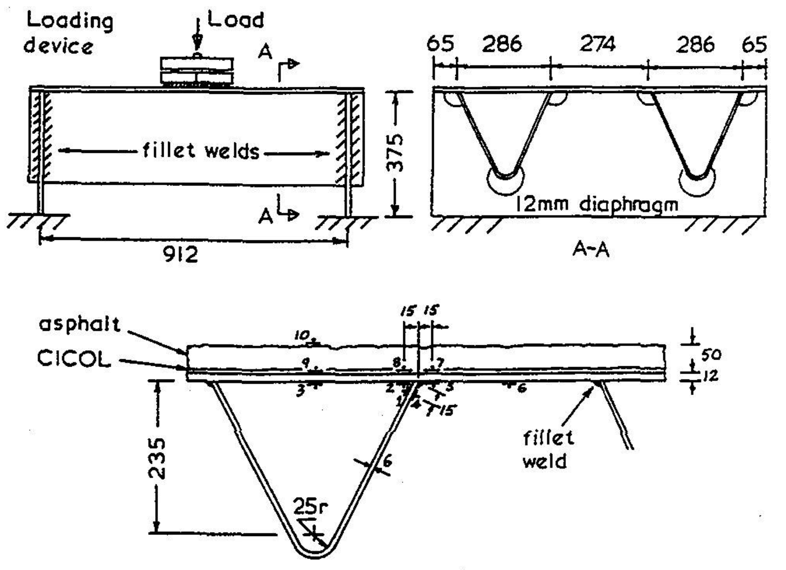


Fig. 5 Full scale test by Smith et all. [9]

Gauge	35°C	15°C	-5°C
1	0.23	0.16	0.11
2	0.23	0.12	-0.16
3	0.30	0.15	0.12
4	0.20	-0.12	-0.14
5	0.36	0.09	0.02
6	0.16	0.05	~0.0
7	0.29	0.02	~0.0
8	0.36	0.11	0.06

Table 2 Reduction factors [9]

Comparible stress reductions were found by Kolstein [6] testing specimens in a temperature range of -25°C up to +40°C. The load signal used has been obtained by analysing strain gauge measurements on an existing bridge.

In this research program also tests have been carried out to improve the fatigue resistance of the traditional mastic asphalt by using modified bitumen. Fatigue test results on two types of mastic asphalt are shown in Fig. 6a and 6b. The dynamic stiffness modulus of the modified type (STY-P1) appeared to be lower than the traditional one (REFB-P1). Considering the results in terms of applied strains the fatigue strength of the modified type is better. However if the results are plotted in terms of applied stresses just the opposite was found. In Fig. 6c the effect of these two materials on a steel deck are shown. It can be noticed that the modified type (STY1) resulted in larger deformations of the steel plate and a fatigue behaviour comparable to the traditional one (REF2). So it was concluded that due to the composite effect it is necessary to require for a modified surfacing layer, besides a better fatigue resistance, at least stiffness moduli which is the same as that of a traditional used surfacing system.

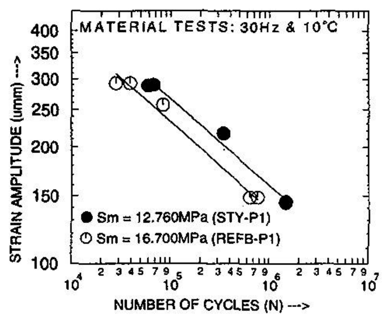


Fig. 6a

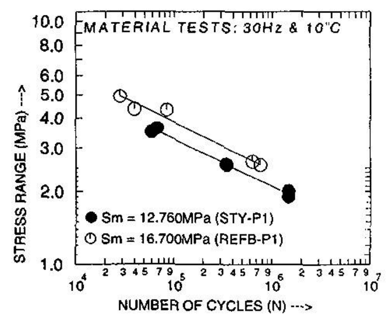


Fig. 6b

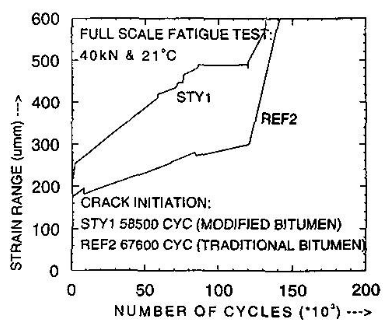


Fig. 6c

4. Site measurements

To obtain information about the composite action of the surfacing on real structures site measurements have been carried out on two highway bridges in The Netherlands. On the first bridge strain measurements have been performed on the unsurfaced bridge deck and the surfaced bridge deck with different surfacing systems (mastic asphalt and a polyurethane system) using a calibrated truck as well as under normal traffic conditions. On the second more heavily loaded bridge strain measurements took place at more locations of the orthotropic deck which have been built up with various plate thicknesses. First results have been published by Kolstein et all. earlier [6, 9]. In this paper the authors concentrate on the influence of the temperature and the steel plate thickness on the stress spectra measured under normal traffic conditions.

4.1 Description and instrumentation of the bridges

4.1.1 Steel structure, surfacing and traffic intensity

The Caland Bridge (Fig. 7) built in 1969 is an important link in the habour area of Rotterdam. It has four traffic lanes, two railway tracks, a bicycle track and a foot path. It is a plate girder truss bridge with four spans. One of them is a vertical lift bridge. The road section consists of a 10mm steel deck plate with closed longitudinal stiffeners. The original surfacing system was based on bitumen binders (mastic asphalt). A part of the surfacing has been replaced by a new system based on polyurethane resins. In both cases the nominal thickness of the total surfacing amounts to 50mm.

The Moerdijk Bridge (Fig. 8) built in 1975 carries the long distance traffic to e.g. Belgium, France and Spain. The truck intensity in the order of 2.10^6 per year in each direction is divided over three traffic lanes. This box girder bridge has 10 independend spans of 100m. The bridge deck consists of an orthotropic steel plate of 10, 12 and 14mm (varying in longitudinal direction) stiffened by trapezoïdal longitudinal stiffeners. The nominal thickness of the mastic asphalt surfacing system is 60mm.

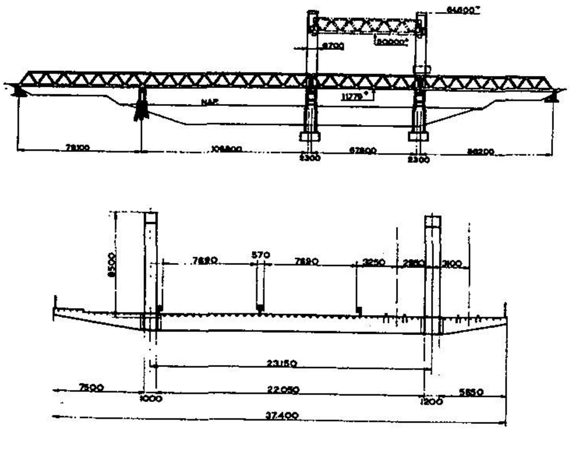


Fig. 7 Calandbridge

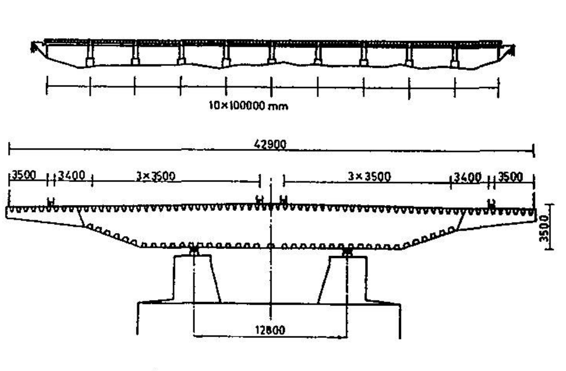
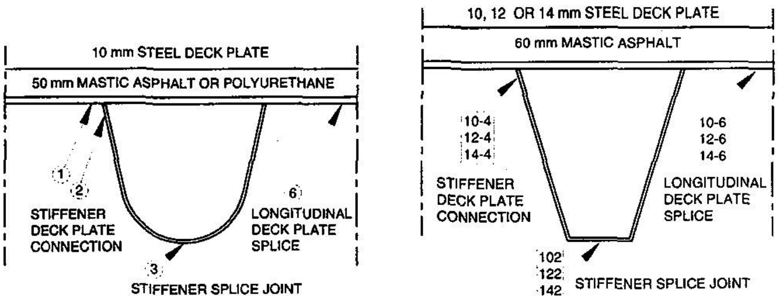


Fig. 8 Moerdijk Bridge

4.1.2 Instrumentation and processing of the data

In several sections of the bridges, various strain gauges were applied in order to obtain an insight in the effect of the surfacing in reducing the strains in the steel deck plate. Most strain gauges were positioned 25mm from the welds between the deck plate and the longitudinal stiffeners, and close to the offside wheel track of the heavy loaded slow lane. Several temperature gauges were attached to the underside of the steel deck plate. Only the locations further discussed in this paper are indicated in Fig. 9.



(a) Caland Bridge (b) Moerdijk Bridge

Fig. 9 Strain gauge locations

The stress variations have been measured under normal trafficking. The range-pair cycle counting method has been used to convert the stress spectra of a complex waveform into a sequence of identifiable cycles to enable Miner's rule to be used to calculate the fatigue damage produced by the spectrum.

4.1.3 Test results

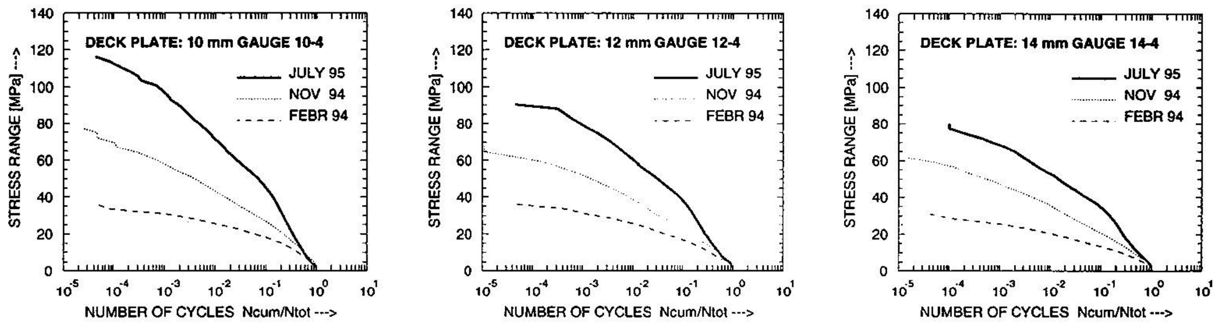
Stress spectra measured on the Moerdijk Bridge at several locations and different cross sections (deck plate of 10, 12 and 14mm) have been summarised in Fig. 10, 11 and 12. These measurements have been carried while the temperature at the underside of the deckplate amounts to be about 35°C (July 95), about 15°C (Nov 94) and respectively 5°C (Febr 94). As mentioned before the thickness of the mastic asphalt surfacing is about 60mm.

For the stiffener deck plate connection (Fig. 10) and the longitudinal deck plate splice (Fig.11) it can be seen that at these locations the influence of the temperature on the stress level is larger than the influence of the thickness of the steel deck. A thicker deck plate reduces the stresses effectively if the temperature is high. This agrees with the conclusions of the theoretical analysis as shown before in Fig. 4. The stress spectra measured at the bottomside of the longitudinal stiffener splice joint (Fig. 12) are less influenced by the temperature. Here there is some influence of the thickness of the steel deck plate.

Using the stress spectra measured in July 95 for the different welded connections the fatigue damage as a function of the fatigue categories according to the ECCS recommendations or Eurocode design rules have been calculated. The results are gathered in Fig. 13 and Fig. 14. From Fig. 13 the effect of the steel plate thickness can be seen clearly. For the stiffener splice joint the effect is neglectible. For the stiffener to deck joint and the longitudinal butt weld the effect is clearly visible. From Table 3 it can be seen that a 20% thicker deck plate reduces the fatigue damage with a factor 1,7 to 5,1. For a 40% thicker plate this factor is about 3,4 to 8,0.

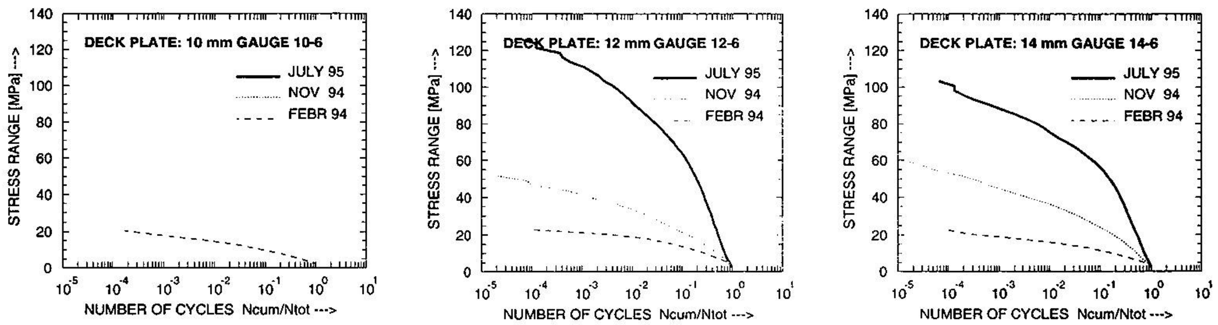
Joint (fatigue class)	Deck plate thickness		
	10mm	12mm	14mm
Stiffener to deck joint			
(EC3-100)	$11{,}3.10^{-5}$	$4{,}13.10^{-5}$	$1{,}42.10^{-5}$
(EC3-56)	$15{,}2.10^{-4}$	$7{,}60.10^{-4}$	$4{,}50.10^{-4}$
Longitudinal deck plate splice			
(EC3-100)		$3{,}60.10^{-4}$	$1{,}36.10^{-4}$
(EC3-71)		$4{,}00.10^{-3}$	$7{,}79.10^{-4}$

***Table 3** Fatigue damage (D3+D5), spectra Moerdijk Bridge over the month July 95*



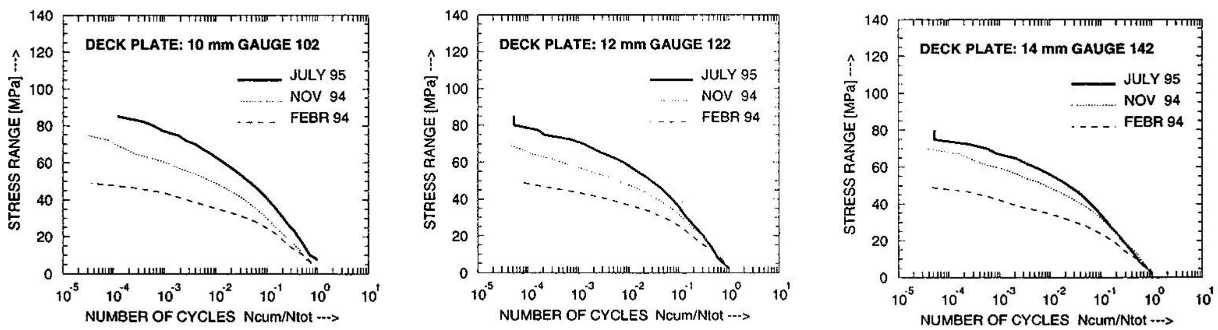
(10a) (10b) (10c)

Fig. 10 Measured stress spectra <u>stiffener deck plate connection</u> - 60mm mastic asphalt surfacing



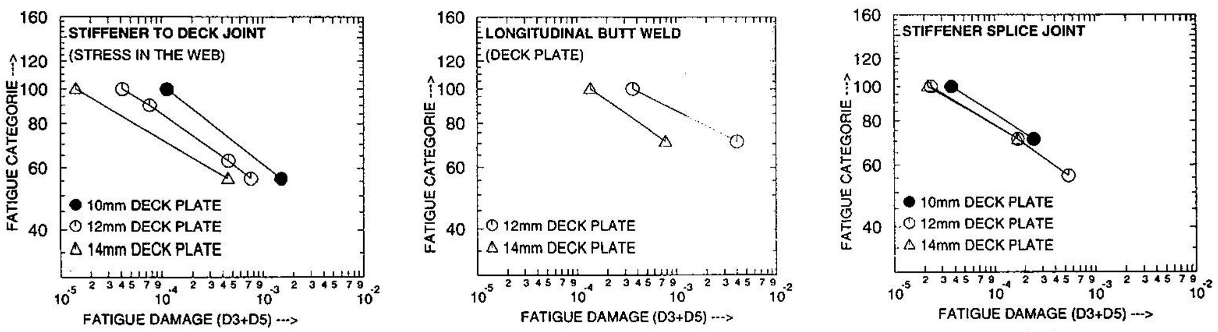
(11a) (11b) (11c)

Fig. 11 Measured stress spectra <u>longitudinal deck plate splice</u> - 60 mm mastic asphalt surfacing



(12a) (12b) (12c)

Fig. 12 Measured stress spectra <u>stiffener splice joint</u> - 60mm mastic asphalt surfacing



(13a) (13b) (13c)

Fig. 13 Damage calculations using EC3 fatigue categories and stress spectra of July 95 .

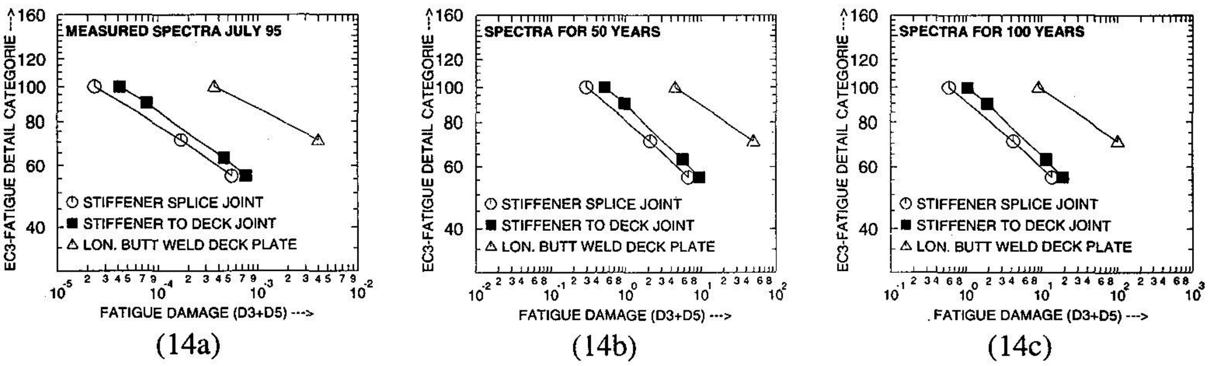


Fig. 14 Damage calculations using EC 3 fatigue categories and stress spectra based of July 95

Considering the fatigue damage for the three different details for the 12 mm deck plate only, from Fig. 14 it can be concluded that the fatigue damage for the longitudinal butt weld in the deck plate is much higher than the fatigue damage for the other two details.

Joint	EC3-Fatigue Detail Category 50 years	100 years
Stiffenener splice joint	80	90
Stiffener to deck joint	90	100
Longitudinal deck platesplice	125	140

Table 4. Required EC3-fatigue detail category

If the measured spectra in July would be representive for the whole life time of the bridge the calculated fatigue damage can be related to a number of years (see Fig. 14b and Fig. 14c). For a "crack free period" of 50 years or 100 years the required fatigue detail categories for the different joints can be calculated and are given in Table 4.

If the results of the stresses measured in e.g. FEBR 94 and NOV 94 (see Fig. 10, 12 and 13) are included in the year spectrum it is clear that the required fatigue categories from Table 4 are much too conservative. The resulting spectra are at such a level that depending on the considered fatigue class all stress ranges are below the constant amplitude fatigue limit. Here the fatigue damage very small or even neglectable.

4.1.3.2 Comparison of stress spectra using different surfacing systems (50mm thickness)

Stress spectra measured on the Caland Bridge at several loctions are given in Fig. 15. It can be seen that at a temperature domain of -5°C up to +23,4°C the stress spectra are influenced only slightly by the level of temperature under the surfacing system which is based on synthetic materials. It is clear that if the stress reducing effect is included in design rules the behaviour of different systems must be included in a proper way.

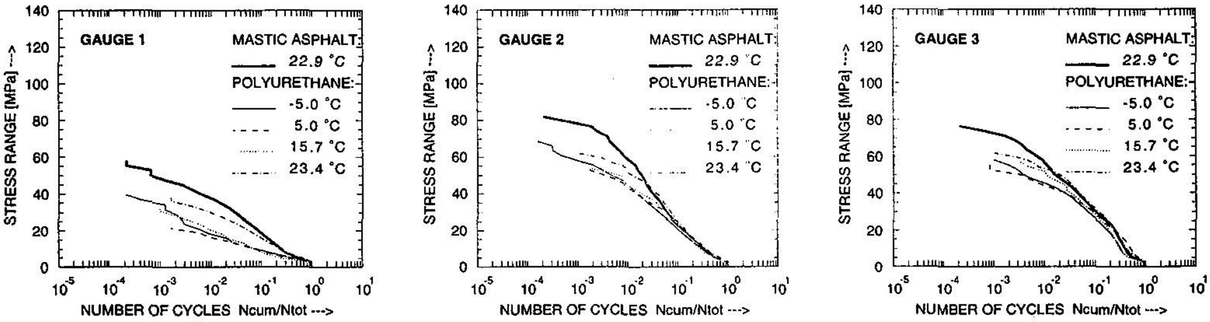


Fig. 15 Measured stress spectra Caland bridge 10 mm deck plate and 50 mm surfacing

5. European Prestandards

5.1 ENV 1991-3 Traffic Loads on Bridges

The dispersal through the pavement and orthotropic decks of the concentrated loads (wheel contact area) of the load models mentioned in Eurocode 1 Part 3 is taken at a spread-to-depth ratio of 1 horizontally to 1 vertically down to the level of the middle plane of the structural top plate below. This rule is only valid for the characteristic loads intended for the determination of road vehicle effects associated with ultimate limit-state verifications and with particular serviceability verifications. This is not applicable for the fatigue load models.

5.2 Draft ENV 1993-2 Steel Bridges

In the current draft of Eurocode 3 Part 2 the longitudinal stiffeners or stringers have to be designed for a minimum stiffness to reduce the flexibility of the steel deck especially close to a hard line support such as a web of a main girder. The required stiffness will be higher for stiffeners adjacent to a web, to reduce the relative deflections and hence the flexural strains in the surfacing. However in the code up to now rules are missing which take count of the composite action of the surfacing with the deck plate.

6. Concluding Remarks

It can be concluded that measurements on existing bridges confirm the theoretical analysis and laboratory tests carried with respect to the composite effect of the surfacing and the orthotropic steel bridge deck. This means that the influence of the thickness of the steel plate is low compared to the influence of the temperature on the composite action of the surfacing and steel plate. Furthermore the behaviour of bituminous surfacing systems differ from systems based on synthetic materials. To be able to quantify the composite action additional measurements and further parametric studies are required. For the design of new bridges and the evaluation of existing bridges it is required to include this effect in the fatigue analysis of welded details of orthotropic steel decks.

Neglecting the surfacing provides a factor of safety of unknown magnitude. If the contribution of the surfacing could be quantified it is possible to take it into account for design purposes, thus leading to a more efficient and hence cheaper structure, although adequate maintenance (including replacement) would be necessary to ensure that its contribution remains effective through the life of the bridge.

Recently in the Netherlands an orthotropic steel deck plate with a thickness of 18 mm and an 8 mm thick synthetic resin wear layer has been built. Compared to an asphalt mastic layer, this provides considerable savings on the structures own weight.

7. Acknowledgements

The authors wishe to thank the Ministry of Transport, Public Works and Watermanagment for their permission to publish this paper.

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