System fatigue assessment of orthotropic steel bridge decks

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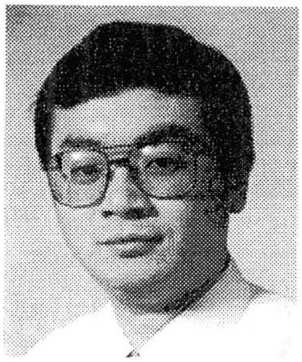
Naxin ZHANG
Research Fellow
TU-Delft
Delft, The Netherlands



Naxin Zhang, born in 1968, received his B.Eng., M.Eng. & Ph.D. in Structural Engineering from Tsinghua Univ., Bejing, China. From 1997 to 1998, he was a research fellow in the Steel Structure Group of TU Delft.

Henk KOLSTEIN
Research Eng.
TU-Delft
Delft, The Netherlands

Henk Kolstein, born in 1952, joined Delft Univ. of Technology in 1971. Since 1978, he has been participating in ECSC research within the domain of bridge loading and fatigue of orthotropic steel bridge decks.

Summary

In the recent research of System Fatigue Durability Assessment for steel orthotropic bridge decks, the SRBA (Systematic Reliability Blocking Analysis) Technique is introduced and developed. This method is summarized as the procedure of *Structure Blocks Decomposition* plus *System Reliability Assembly*. So the structural redundancy and systematic scale are no longer the great worry of system reliability calculation, and the repairing effect becomes free to be involved. This paper gives an outline of the investigation. An example with on-site measured data is also presented for evaluating its system fatigue life and reliability.

1. Introduction

The steel orthotropic bridge deck is a welded structure comprising of the deck plates, deck stiffeners (or troughs), crossbeams, and main girders. The previous connection designs usually can not meet the fatigue durability demands. With the sponsor of ECSC (European Coal and Steel Community), a series of collaborative projects concerning such deck structures have been carried out in Europe. Topics covered the traffic loading, resulting stresses and detail fatigue strength, etc [1]. Nevertheless, the fatigue assessment is still stay at a componental or elemental level. That means the estimate life of a typical joint is taken as the deck integral service life.

During the componental fatigue S-N design or assessment, 95% is specified to be the confidence interval of reliability, which indicates that around 5 over (per) 100 joints might be failed during the service life. Normally there are several hundreds joints, with almost the same constructional detail and similar fatigue loading, inside the orthotropic bridge deck system. So, the elemental design, which is regularly believed safe enough for the individual elements, becomes unreliable for the whole deck system.

There are some difficulties in the systematic fatigue analysis for orthotropic decks, for instance, the very large quantity of similar joints, uncertain sequence and relationship among the damage of elements, and fuzzy criterion of the system failure, etc. Considering these characteristics, the Systems Reliability Blocking Analysis (SRBA) technique [3] was adopted to the deck system fatigue assessment. The integral structure is treated as a multi-leveled composition of chains of serial/parallel blocks (subsystems). The individual welded joint is taken as the elemental block, whose reliability can be determined by the conventional method. By the assumed subsystem-assembling models, the system reliability could be derived from elemental ones level by level.

Because of the processing with subsystems, the structural redundancy is no longer a big trouble and the repairing influence becomes easy to discuss. Comparing with current system reliability methods, the computing amount of SRBA is much less, while the credibility of its result is not lost [4]. It has remarkable fitness to engineering applications, extremely for the structures which are comprised by lots of constructional-alike parts or elements.

2. System Fatigue Assessment Method for Orthotropic Decks

2.1 Subsystems decomposition

The System Blocking Procedure for orthotropic decks can be standardized to a three-leveled decompositions [4]. During every decomposition, the nascent system, ranked with the upper level, is divided into a series of blocks (or subsystems) taking up the next level.

1st-level subsystems: The bridge deck system visibly and functionally involves several traffic lanes. Different lanes normally expect similar constructional details, but different traffic loading. Sometimes the constructional style or details are segmental continuous along the bridge, for instance, the thickness of the deck plates are alternating. Each of the lanes or lane-segments could be taken as an individual 1st-level block, although there is some kind of coherence among their failure states. From the serviceability point of view, if anyone of the lanes or lane-segments suffers severe damage, the brige deck structure could be thought of failure and need repair. So, the 1st-level blocks are supposed cascade (or serial) to each other in the composition of integral system.

2nd-level subsystems: Every lane or lane-segment contains several *joint-groups* (the sets of joints with same type and constructional details) which might incur fatigue damage, such as the groups of (a) stiffener splice joints, (b) stiffener to deck joints, (c) stiffener to crossbeam joints, (d) deck plate splices, (e) crossbeam to deck joints, and (f) main girder to deck joints, etc. Sometimes one sort of joints consist of one or several joint-groups. Such joint-groups are taken as the 2nd-level blocks, and they are simply assumed serial to each other. A 2nd-level subsystem possesses a large number of joints with same typical construction and same simplified loading model.

3rd-level subsystems: Each joint-group holds only one *typical joint* as the representative, which is taken directly as the 3rd-level block. The fatigue behavior of typical joints, containing the details which propagate fatigue cracks, could be examined by the S-N tests.

2.2 System failure criterion and Bernoulli distribution assumption

For the fatigue of deck system, there is no clear definition of system failure.The common limit of no crack occur can be taken as a system safety index. Correspondingly the system reliability is represented by the *Probability of First Cracking* (PFC), which expects no more than one joint suffers fatigue damage. This index is very sensitive to the quantity of concerned joints. Normally it is not economic to keep every joint reliable during the whole service life.

From the deck serviceable and repairable demand, a few of joints damaged is allowed and does not affect the structural integrity. Therefore, the indexes of percentile joints failure are more suitable for the deck system. The system reliability can be represented by the *Probability of z% Joints Damage* (PJD- *z*%), which intends no more than *z*% of total joints are failed. Another benefit of such indexes is their insensitiveness to the system scale. It need more discussion and experience to select a proper percentage as the system failure limit. PJD-0.5% and PJD-1% are recommended here as the failure limit of joint-groups of steel orthotropic decks.

The orthotropic deck system contains particularly a large number of elemental joints, most of them are working in several typical cases of consistent constructional details and similar stressing conditions. These joints act as the same functions and endure with roughly the same loading histories, wherever their locations are along the bridge deck. From the statistical point of view, it is reasonable to assume that the fatigue failure of a deck joint-group, which is taken as the damage occuring in a certain number of its joints, approximately follows the Bernoulli Distribution, and the reliability of a joint-group is then computable by the *Bernoulli Formula*.

2.3 System reliability calculation

The reliability assembling procedure, inverse to the sequence of system blocking, is carried out from lower level to upper level [4].

According to the schedule of fatigue S-N analysis and First-Order-Second-Moment probabilistic estimation, the elemental reliability can be derived [3,4] if the statistical data of S-N tests (for the resistance) and stress measurement (for the loading) are provided. Generally, the resistance and loading are assumed following the Log-normal Distribution.

With the hypothesis of Bernoulli Distribution of joint-groups failure, the 2nd-level reliability can be determined if the elemental reliability and joints quantity are known. Taking PJD-z% as the subsystem reliability of a joint-group, the 2nd-level reliability is formulated by

$$R_{i\text{-}2nd} = \sum_{x=0}^{m} C_n^x \cdot p_e^x \cdot (1-p_e)^{n-x} \quad \text{and} \quad C_n^k = n!/(n-k)!k! \tag{1}$$

where n is the joints quantity of the joint-group, excluding the eliminable portion; $m = \lfloor n_s \cdot z\% \rfloor$ is the limit number of failed joints; n_s is the sum of joints in the joint-group, including the eliminable portion; and p_e is the failure probability of the typical joint.

After getting the reliability of all 2nd-level subsystems, the 1st-level and the integral reliability can be determined in subsequence. Noting $\bar{\beta} = (\beta_1, \beta_2, \cdots, \beta_n)$ as the subsystems reliability index vector, the system reliability can be obtained in approximation [3,4]:

$$R_{\text{serial}} = \Phi_n(\bar{\beta}, \rho) \quad \text{and} \quad \Phi_n(\bar{\beta}, \rho) = \int_{-\infty}^{\infty} \phi(t) \prod_{i=1}^{n} \left[\Phi\left(\frac{\beta_i - \sqrt{\rho}t}{\sqrt{1-\rho}} \right) \right] dt \tag{2}$$

where $\Phi_n(*,*)$ is the cumulative function of Standard N-dimensional Normal Distribution, $\phi(\cdot)$ and $\Phi(\cdot)$ are respective the density and cumulative function of Standard Normal Distribution. The correlation coefficient ρ describe the linear similarity and inclusiveness among the failure states of the blocks within same level. The equivalent average correlation coefficients for the SRBA of orthotropic decks are investigated and suggested in [4].

2.4 Repairing consideration

The reliability assembling process depends only on the systematic blocking diagram and its probabilistic model, so it is easy for the SRBA to access the repairing discussion. After a repair of some deck joints within same joint-group, a new joint-group composed of these repaired joints is added to the 2nd-level blocks. Sometimes the repaired joints cover different joint-groups, then several repaired joint-groups will arise. Every repaired joint-group belongs to its original 1st-level subsystem. The repaired joint-group has a individual calendar of servicing to calculate their elemental reliability of typical joint.

3. Example

3.1 Measured data

The example bridge [2] is shown in Fig.2, which was built in 1975. The truck intensity in the order of 2×10^6 per year in each direction is divided over three traffic lanes. The bridge deck consists of an orthotropic steel plate (of 10, 12 and 14mm varying in longitudinal direction) stiffened by the longitudinal trapezoidal troughs.

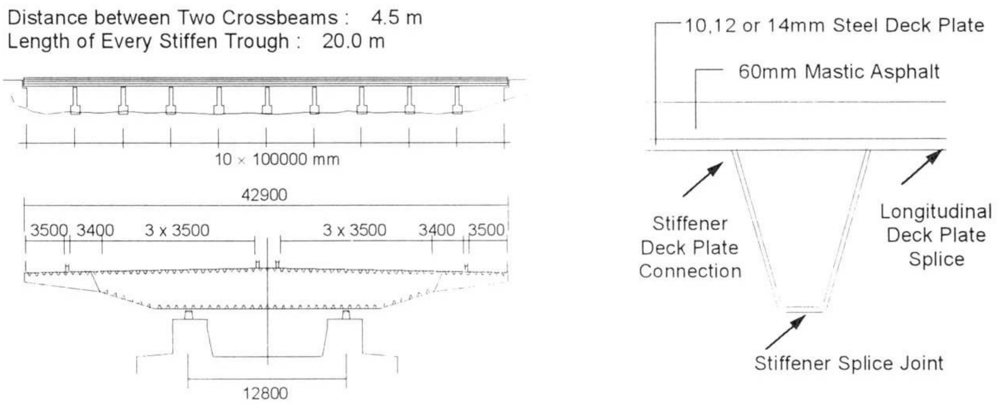


Fig. 1 *Example bridge and its orthotropic deck*

The stress spectra had been measured in three temperature conditions [2]. The equivalent stress-ranges with the corresponding fatigue detail classification are summarized in Table 1. The stress value of whole year takes an weighted average of [0.25(*Feb*)+0.5(*Nov*)+0.25(*Jul*)]. Table 2 shows the amount of several sorts of deck joints in evaluation. The non-uniformity in loading distribution and welding workmanship are regarded here, e.g. the *Elim. Factor* in Table 2.

Constructional Details		Load (from measurements)					Resistance (from tests)	
		Equivalent Stress Range				Stress Cycles per Year	Detail Class (Suggested)	Deviation of (logN)
		Feb(5°C)	Nov(15°C)	Jul(35°C)	Year			
Stiffener Splice Joints	deck plate 10mm	19.7	26.3	34.5	26.70	1.628 e6	71	0.2325
	deck plate 12mm	20.5	26.2	31.2	26.02			
	deck plate 14mm	19.0	26.8	29.9	25.62			
Stiffener to Deck Joints	deck plate 10mm	14.2	23.4	39.2	25.05	1.870 e6	56	0.3918
	deck plate 12mm	13.6	20.5	32.9	21.87			
	deck plate 14mm	10.8	18.8	29.0	19.35			
Longinal. Deck Plate Joints	deck plate 10mm	8	-	-	≈25.	1.450 e6	80 (or E in BS5400)	0.2510 (BS5400)
	deck plate 12mm	9	18	52	24.25			
	deck plate 14mm	9	20	44	23.25			

Table 1 *Results from on-site measurement and ECSC tests*

	Stiffener Splice Joints	Stiffener to Deck Joints	Stiffener to Crossbeam Joints	Longitud. Deck Plate Joints	Crossbeam to Deck Joints
n_s : Each Lane	200	1600	3200	200	1600
LaneSegment-10mm	40	320	640	40	320
LaneSegment-12mm	80	640	1280	80	640
LaneSegment-14mm	80	640	1280	80	640
n_s : Σ(6 lanes)	1200	9600	19200	1200	9600
Elim. Factor (1- n/n_s)	1/2	1/2	2/3	1/2	2/3

Table 2 *Amounts of deck joints in consideration*

3.2 Conventional fatigue assessment for typical joints

It is supposed by experience that the variation coefficients of the measured stresses on the details of Stiffener Splice Joints, Stiffener to Deck Joints and Longitudinal Deck Plate Joints are 0.050, 0.075 and 0.10 respectively. Table 3 shows the results of failure probability of typical joints at several intervals of bridge service time. From the elemental assessment, the fatigue life of the deck is about 68 years, governed by the Stiffener to Deck Joints with the 10mm thick deck plate.

Service time (years)		25	30	35	40	50	60	70	100
Stiffener Splice Joint	deck plate 10 mm	.00002	.00005	.00013	.00029	.00097	.0024	.0048	.0205
	deck plate 12 mm	.000007	.00002	.00006	.00014	.00049	.0013	.0027	.012
	deck plate 14 mm	.000004	.00001	.00004	.00009	.00032	.00085	.0018	.0092
Stiffener to Deck Joint	deck plate 10 mm	.0047	.0076	.0113	.0155	.0258	.0379	**.0514**	.0973
	deck plate 12 mm	.00061	.0011	.0018	.0026	.0049	.0079	.0117	.0270
	deck plate 14 mm	.00007	.00014	.00024	.00038	.00080	.0014	.0022	.0061
Longitud. Deck Plate Joint	deck plate 10 mm	.000005	.00001	.00002	.00004	.00010	.00022	.00040	.0014
	deck plate 12 mm	.000002	.000005	.00001	.00002	.00005	.00012	.00022	.00084
	deck plate 14 mm	.000001	.000002	.000004	.000008	.00002	.00005	.00009	.00039

Table 3 *The elemental fatigue failure probability of typical deck joints*

3.3 System fatigue assessment

For simplicity, suppose the 6 traffic lanes of the bridge carry a same traffic model. The thickness of deck plate is varied among 10, 12 and 14mm, consequently three lane-segments are identified (see Fig.5). Only three sorts of joints are measured and can be taken into evaluation, then there are altogether 9 joint-groups, which are regarded as the 2nd-level blocks (see Table 4). For more discussions, three system safety indexes for joint-groups, i.e. PFC, PJD-0.5% and PJD-1%, are selected in the reliability calculation. All the systematic analysis results are shown in Table 4 & 5.

Servicing time (years)		25	30	35	40	45	50	60	70	100
Stiffener Splice Joint-Group with Deck 10mm	PFC					1.	0.994	0.966	0.886	0.292
	PJD-0.5%					1.	0.994	0.966	**0.886**	0.292
	PJD-1%						1.	0.997	0.979	0.553
Stiffener Splice Joint-Group with Deck 12mm	PFC						1.	0.960	0.862	0.216
	PJD-0.5%						1.	0.996	0.972	**0.449**
	PJD-1%							1.	0.999	0.836
Stiffener Splice Joint-Group with Deck 14mm	PFC							1.	0.930	0.351
	PJD-0.5%							1.	0.990	**0.620**
	PJD-1%								1.	0.927
Stiffener to Deck Joint-Group with Deck 10mm	PFC	0.060								
	PJD-0.5%	0.983	**0.800**	0.356						
	PJD-1%		1.	0.992	0.883	0.507	0.140			
Stiffener to Deck Joint-Group with Deck 12mm	PFC	1.	0.376	0.140						
	PJD-0.5%					1.	0.998	**0.866**	0.272	
	PJD-1%							1.	0.999	0.026
Stiffener to Deck Joint-Group with Deck 14mm	PFC						1.	0.251	0.076	
	PJD-0.5%								1.	0.983
	PJD-1%									1.
Longi. Deck Plate Joint-Group with Deck 10mm	PFC								1.	0.987
	PJD-0.5%								1.	0.987
	PJD-1%								1.	0.999
Longi. Deck Plate Joint-Groups with Deck 12 &14 mm	PFC									1.
	PJD-0.5%									1.
	PJD-1%									1.

Table 4 *The system reliability of the 2nd-level blocks*

Servicing time (years)		25	30	35	40	45	50	60	70	100
Lane-Segement of Deck Plate Thickness 10mm	PFC	0.060								
	PJD-0.5%	0.983	**0.800**	0.356						
	PJD-1%		1.	0.992	0.883	0.507				
Lane-Segement of Deck Plate Thickness 12mm	PFC	1.	0.376							
	PJD-0.5%					1.	0.998	**0.886**	0.270	
	PJD-1%							1.	0.998	0.
Lane-Segement of Deck Plate Thickness 14mm	PFC						1.	0.251		
	PJD-0.5%							1.	0.990	**0.620**
	PJD-1%								1.	0.927
Deck Integral	PFC	0.060	-							
	PJD-0.5%	0.983	**0.800**	0.356	-					
	PJD-1%	1.	1.	0.992	0.883	0.507	-			

Table 5 *The system reliability of the 1st-level blocks and integral structure*

The estimated fatigue life of the integral deck system is around 28 years, providing PJD-0.5% as the safety index of joint-groups and 0.9 as the integral reliability criteria. The ratio of the service lives predicted by systematic assessment and elemental assessment is about 0.41. If take PJD-1% as the group safety index, the deck servicing years is computed to 39, which is nearly 1.4 times than the result under the selection of PJD-0.5%. The first fatigue crack might appear, most probably among the Stiffener to Deck Joints with 10mm deck plate, after 20~25 years in-service.

4. Conclusions

1) The SRBA is a system reliability approach to structural fatigue assessment. Its main parts are the system-blocking and reliability-assembling procedures, which are flexible to nearly all kinds of structures. The SRBA procedures need not a large amount of computation, and are capable to include the repairing consideration.

2) The failure of a deck joint-group is defined as the damaged joints reach to a certain percentage, and assumed following the Bernoulli Distribution.

3) The system reliability depends on not only its elemental standard, but also the system scale and composition. Systematic effect, here especially the statistical effect, is remarkable and could not be ignored in the fatigue assessment of orthotropic bridge decks. From the example, the system fatigue life is about 28 (or 39) years, while the elemental estimated life is about 68 years. The difference is more than 2 times. Due to the large quantity of joints within deck structures, the system reliability decrease much rapidly near the end of its service life.

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