COMPARISON BETWEEN DIFFERENT METHODS FOR FATIGUE LIFE PREDICTION OF BOGIE BEAMS

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ABSTRACT

In this paper a recently proposed method for fatigue life prediction based on level crossing, the HdM-method, and a modification of the method are used to predict the fatigue life of two different types of bogie beams. The results of the fatigue life predictions are compared with experimental results and with fatigue life predictions made with the S-N method and the fracture mechanics method.

The life time predictions made with the modified HdM-method agreed rather well with experimental results for the first type of bogie beams, while the method underestimated the fatigue life for the bogie beams of the second type with a factor of up to 50. This is probably due to differences between the two types of load sequences used during the two tests in variables, such as irregularity factor and block length. The life times for the second type of bogie beams were rather short compared to the block length which led to a situation where the level of the crack closure stress was not constant during the test. Both the S-N method and the fracture mechanics method overestimated the fatigue life of both types of bogie beams.

This study shows that the modified HdM method may be used for conservative fatigue life predictions, if the life times are long enough and the S_{op}-value may be considered as constant during the load sequence, in other words, if the plastic zone is much larger than the increase in fatigue crack length caused by the fatigue crack propagation during a load sequence.

Keywords: Fatigue, Life time predictions, Bogie Beams, Welded steel, Spectrum Load, Crack closure, Level crossing

NOMENCLATURE

LEFM =	Linear fracture mechanics	S, S_{max}, S_{min} =	Stress, maximum stress, minimum stress
FEM =	Finite element method	S_{op} =	Crack opening/closure stress
PWT =	Post weld heat treated	N, N_f, N_p =	Number of cycles, number of cycles to fracture during fatigue tests, predicted fatigue life
HdM =	The Holm de Maré method for fatigue life prediction	n_i =	Number of cycles on a stress level
$s_{0.2}$ =	Yield strength	Δs_{eq} =	Equivalent stress range
s_u =	Ultimate strength	ΔK_{th} =	The threshold value
I =	Irregularity factor	α =	The constant in the S-N equation
f =	Frequency	β =	The exponent in the S-N equation
VA =	Variable amplitude loading	C =	Weld category factor according to Swedish Regulations for Steel Structures
CA =	Constant amplitude loading	WB, WC =	Classification of the weld quality
R =	Stress ratio		

INTRODUCTION

Fatigue design of vehicle components is a problematic area for the designer. Two main reasons for this are that vehicle components are subjected to loads with variable amplitude and that the load sequences often are very long. These problems are especially pronounced for components in railway applications, where the fatigue lives are at least several tens of million cycles and where there are relatively few large overloads in a load sequence of more than a million cycles, which give extreme sequential effects. Due to these problems there is no "perfect" design method for railway components even though fatigue of railway components has been studied since the middle of the 19th century.

Today there is a variety of fatigue design methods in use. The best method at present is probably the fracture mechanics method, sometimes combined with the LCF-method, but it is a complicated method and it needs rather exact materials data and good knowledge about the loading conditions. In practical applications the most used fatigue design methods are those which use some sort of S-N-data and the Palmgren-Miner rule for damage accumulation. In many cases the S-N data are standardised design curves. These methods are simple to use but do often give less accurate life predictions [1-3].

A new method for fatigue life predictions, in the following denoted as the HdM-method, has been put forward by Holm and de Mare' [4]. It is based on four assumptions: the damage accumulation rule and the time invariance principle, any stress change causes damage and there is no damage occurring at infinity. When the fatigue life is predicted with the HdM-method a S-N-curve for the material and the result of a level crossing count of the load signal is used. This method and a modification of it, taking crack closure effects into account, has shown promising results when used for fatigue life predictions of different test specimens made of steel [5-7]. The modification uses an empirical formula for calculating a constant mean level of the crack closure stress. Even though the results are promising a new fatigue design method can not be used for design of real components before it has been tested with a large amount of data from fatigue tests made on tests specimens as well as data from full-scale tests of components. By using the new method for different loading conditions and for different materials and specimens the limitations and assets of the method are evaluated.

In this paper the HdM method and the modification of the method are used to predict the fatigue life of two different types of bogie beams. The results of fatigue life time predictions are compared with test results from full-scale tests of the components and with life predictions made with the S-N-method and the fracture mechanics method. The fatigue test and the life predictions, except the life predictions made with the HdM-method and the modification of the HdM-method, are taken from the literature.

EXPERIMENTAL PROCEDURE

Experimental results for two different types of bogie beams were used in this study. Both types of bogie beams were made of welded steel. The first type was tested by ABB Corporate Research and the second type was tested by SP, Swedish National Testing and Research Institute. The first type will further on be called bogie beam 1 and the second type will be called bogie beam 2. The fatigue tests and the life time calculations made with the fracture mechanics method and the S-N-method are presented in [8-9]. Here a short review of the methods, the test specimens and the load sequences is given.

The first types of bogie beams was made in half-scale by section and with full thickness. The beams were made as box beams and were manufactured in three different workshops. The steel used was a weldable micro alloyed steel, Swedish standard SS 2134-01, which approximately corresponds to ISO steel grade E355. The chemical composition and mechanical properties of the steel is presented in table 1. The beams were manually arc-welded and the quality of the welds were set to WB according to Swedish standard SS 06 61 01 [10]. After the welding the beams were stress relieved. The bogie beam is shown in figure 1.

Bogie beam 2 was a bogie beam from a subway train. The bogie consisted of two side beams and a middle beam that connected the side beams. The tested beams were side beams with just a small part of the middle beam attached to them. The beams were welded and the steel used was a SS 2132 steel. The chemical composition and the mechanical properties of the steel is presented in table 1. Two of the beams were stress relieved after the welding. The stress relieved bogie beams were classified as WC and the two others were classified as WB according to SS 06 61 01. The difference in weld classification was probably due to different manufacturing occasions and not to the stress relieving treatment. The beam is shown in figure 2.

Twelve bogie beams of the first type were four point bend tested in an electro-hydraulic testing machine with a frequency of 20 Hz. Three beams were tested with constant amplitude,

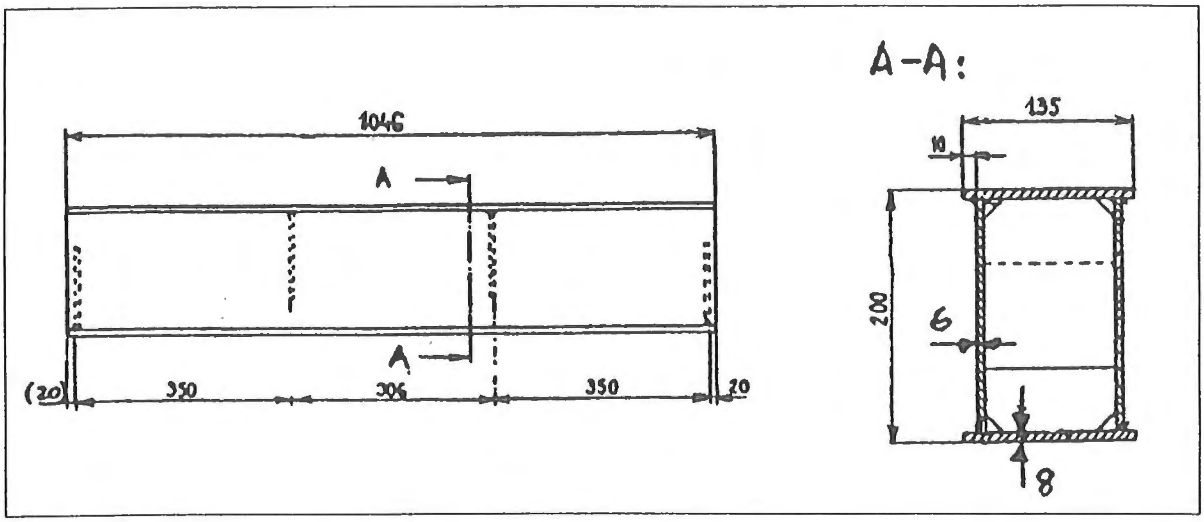

Figure 1. Bogie beam 1. From [8].

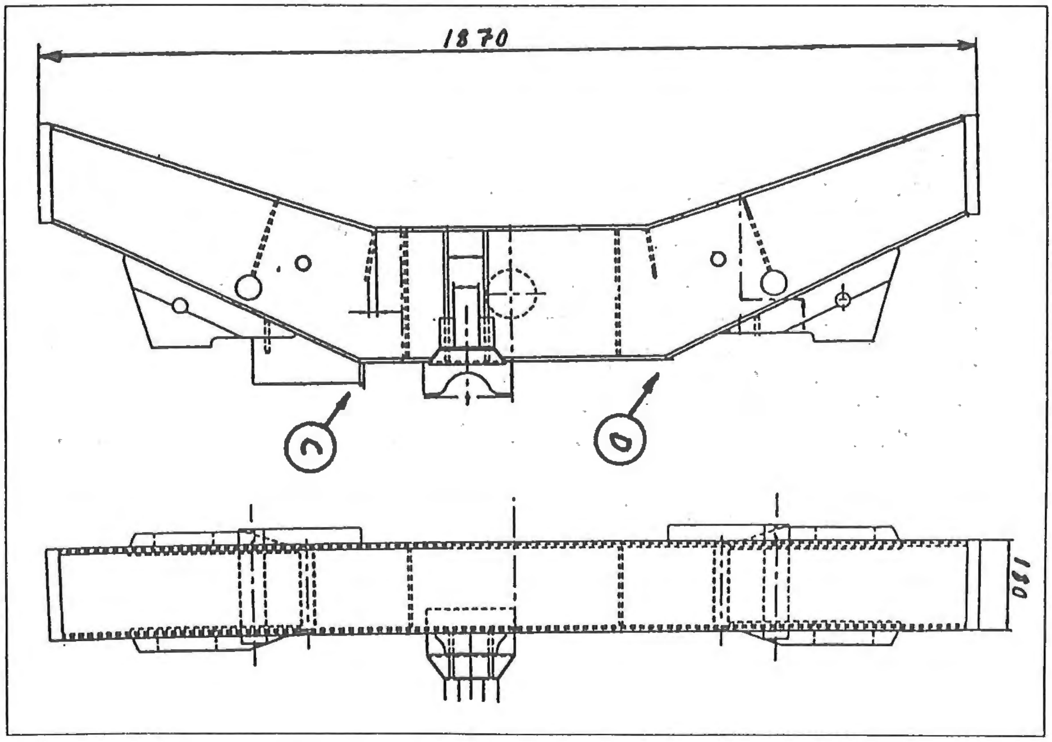

Figure 2. Bogie beam 2. From [9].

Table 1. Chemical composition and mechanical properties of the steels used in the bogie beams.

Bogie beam type	Material	$s_{0.2}$ (MPa)	s_u (MPa)	C (%)	V (%)	Nb (%)	Si (%)	Mn (%)	P (%)	Weld class	Comment
1 (12)	SS 2134-01	410	551	0.20	0.15	0.015	0.5	1.6	0.035	WB	All PWT
2 (4)	SS 2132	375	530	0.20	0.15	0.015	0.5	1.6	0.035	2 WB 2 WC	2 PWT

Figures in brackets are the number of tested specimens.

Table 2. Test parameters used during fatigue tests of the bogie beams.

Bogie beam	s_{max} (MPa)	Δs_{eq} (MPa)	f (Hz)	Type of loading	Irregularity factor	Comments
1 (4 beams)	368	44.9	20	VA	1	
1 (4 beams)	322	39.2	20	VA	1	
1 (1 beam)	315	65.9	20	VA	1	Omitted
1 (3 beams)	226	152	20	CA	1	
2 (4 beams)	275	38.8	5	VA	0.456	

Δs_{eq} is defined in for example [14].

S_{max} = 226 MPa, while the rest were tested with a spectrum load. The load signal during variable amplitude testing was created by using a "drawing without replacement algorithm". The blocks consisted of 268.200 cycles. The load sequence had an irregularity factor close to one. Two different maximum stress levels were used in the variable stresses amplitude tests, 322 MPa and 368 MPa respectively. The load sequence was typical for railway applications with a lot of small load cycles and a few large overloads. The load spectrum for the load signal is shown in figure 3. The other test parameters are shown in table 2.

The subway train bogie beams were tested with a computer controlled servohydraulic actuator in a four point bending fixture. The load signal was originally recorded during a normal subway journey in Stockholm. Then the load signal was edited and a load signal with an irregularity factor of 0.456 and with a load spectrum shown in figure 4 was achieved. The original load sequence included about 500.000 load cycles [9]. The maximum load during the tests was 370 kN which corresponds to a stress level of 275 MPa in the most stressed parts. The other testing parameters are reported in table 2.

LIFE TIME PREDICTIONS

The fatigue life of bogie beam 1 was predicted with four different methods: the S-N-method, the fracture mechanics method, and the modification of the HdM-method with different values on the crack closure stress level. The predictions made with the two first methods were made by ABB Corporate Research and is reported in detail in [8].

The S-N-method calculation was made in accordance with the Swedish design code, BSK [11]. The S-N-curve had three different slopes. The first part of the S-N-curve was extrapolated from the mean value from the CA-tests and with the same slope as Gurney and Maddox [12] found when they fatigue tested manually welded I-beams. The slope was 3. The S-N-curve had a change in slope at $5 \cdot 10^6$ cycles and a cut-off-limit at $1 \cdot 10^8$ cycles as it is prescribed in the Swedish design code.

A fracture mechanics life time prediction was made using Paris' law and linear accumulation of fatigue damage. In the calculations different factors were used to take geometry effects into

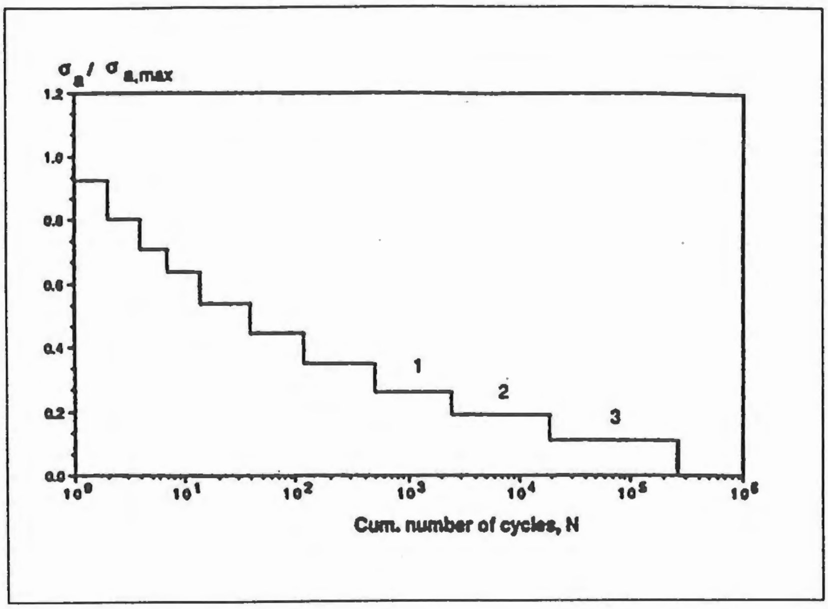

Figure 3. The load spectrum for the load sequence used for testing of bogie beam 1. $s_{a,max}$ was 322 MPa and 368 MPa respectively during the tests. From [8].

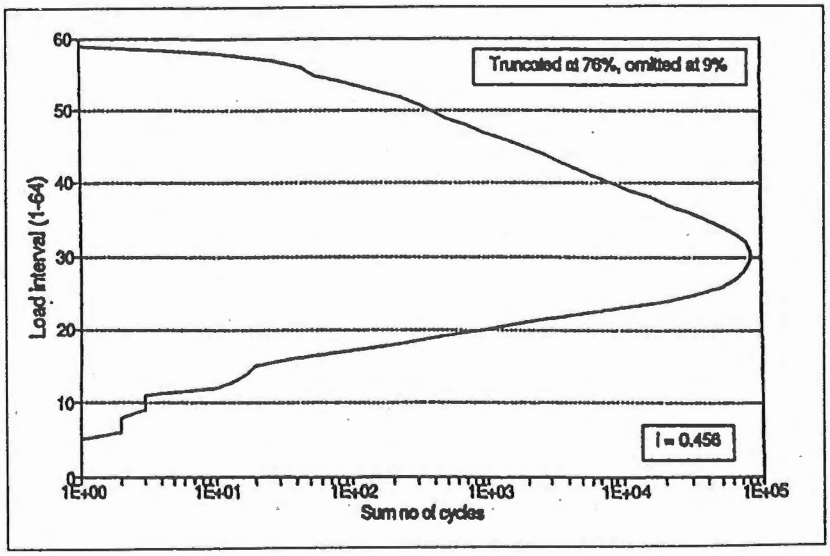

Figure 4. The level crossing spectrum for the load sequence used for testing of bogie beam 2. 60 on the vertical axes corresponds to a load of 370 kN, which results in a stress of 275 MPa and 0 on the vertical axes corresponds to a load of 0. From [9].

account. The fatigue threshold value was taken into account. Only cycles above the fatigue threshold was included. Three different threshold values, ΔK_{th}, were used in the calculations.

Finally the modified HdM-method was used to calculate the fatigue life of the bogie beams. Crack closure was taken into account by using a formula suggested by Maddox et al [13]. The crack closure value is approximated with a constant in the modified HdM-method. To do this simplification it is necessary that the crack closure level is rather constant during time and that is the case if the load sequences are short or if there are "few" cycles between large stress peaks. The formula is derived from crack closure tests performed in different welded constructional steels:

$$S_{op} / S_{max} = 0.24 + 0.47R + 0.28R^2 \qquad (1)$$

Two, rather formal, calculations were made. First, an average R-value for a variable amplitude load was calculated for every single load cycle that occurred in the load sequence. This was made according to equation (2), from for example [14]:

$$R = \frac{\Sigma R_i n_i}{\Sigma n_i} \qquad (2)$$

The R_i -values vary between 0 and 0.8. Applications of (2) gives R = 0.79 and an S_{op}-value of $0.8 \cdot S_{max}$, according to (1). This is not physically reasonable because the crack would only be open during a few per cent of all cycles. It is also demonstrated in [8] that stress ranges as small as one fourth of the constant amplitude fatigue limit influence the fatigue lives of the tested specimens.

Hence, an S_{op}-value was instead calculated for every single load cycle using the R-value and S_{max} for the single cycle and equation (1). This was made in accordance with equation (3):

$$S_{op} = \frac{1}{N}\Sigma(0.24 + 0.47R_j + 0.28R_j^2)S_{j\max} \tag{3}$$

where R_j and $S_{j\max}$ are the R-value and the maximum stress for the single load cycle. Then the S_{op}-value was divided by the maximum stress level occurring in the whole load block. In this way the S_{op}-value for the whole block became $0.43 \cdot S_{max}$.

A simpler and physically more feasible way of estimating S_{op} is to only take the greatest load cycle into account, representing the most important plastic deformation giving cause to crack closure. The R-value in equation (1) is set to S_{min}/S_{max} where S_{min} and S_{max} is the lowest respectively the highest stress level in the whole load sequence. This way of estimating the S_{op} gave a S_{op}-value of $0.24 \cdot S_{max}$. The best approximation of a mean value of S_{op} does probably lie somewhere between 0.24 and 0.43 of S_{max} with 0.24 S_{max} as the lowest possible level and 0.43 S_{max} as the highest possible level.

Since no S-N-curve had been experimentally determined the equation for the S-N-curve, equation (4), had to be estimated for bogie beam 1. This was done with results from constant amplitude tests, just performed on one stress level, and by using an exponent of -3, this gave equation (5).

$$N = \alpha \cdot S^{-\beta} \tag{4}$$

$$N = 6.567 \cdot 10^{13} \cdot S^{-3} \tag{5}$$

In order to study the influence of S_{op} on predicted fatigue life, different values of S_{op} were used during the fatigue life calculations. S_{op} was varied between 0, the same as in the original HdM-method, and 0.5 with a step of 0.05.

The fatigue life of bogie beam 2 was also predicted in three different ways, namely with the S-N method, the fracture mechanics method and the modified HdM-method. The predictions made with the S-N method are based on nominal stress currently adopted in several design codes, for example BSK [11], BS [15] and Eurocode [16]. When the fracture mechanics method was used both the stresses in the bogie beam and the geometry factors were calculated with FEM. The predictions made with both the S-N method and the fracture mechanics method are described in detail in [9].

The equation for the S-N-curve used in the modified HdM-method was the same as the one used for the S-N-calculations, taken from BSK [11] where a fracture probability of 2.3 % is used for fatigue design. The S-N-curve was then changed to 50 % fracture probability by moving it two standard deviations to the right. The C-value was assumed to 45. This gave the following equation:

$$N = 4.92 \cdot 10^{11} \cdot S^{-2.96} \tag{6}$$

Also in this case S_{op}-calculations according to (1) - (3) appears to yield unrealistic results. Therefore life times calculation for three different S_{op}-values, 0, 0.24 and 0.5, are reported. $S_{op} = 0$ was chosen because it is same as the original HdM-method, $S_{op} = 0.24$ was chosen because when only the largest load cycle in the load sequence was taken into account it gave this S_{op}-value, in the same way as for bogie beam 1. Since the irregularity factor for the load sequence used for testing of bogie beam 2 was 0.456 it was not possible to use the range pair count to calculate the maximum S_{op}-value as for bogie beam 1. However since the range pair spectrum are rather alike and the number of small cycles occurring above the mean level are about the same as the number of small cycles occurring below the mean level it was considered that 0.5, which is close to 0.43 achieved for bogie beam 1, is taken as a estimate of the highest possible S_{op}-value in the load history.

RESULTS

The results from the fatigue tests of bogie beam 1 are presented in table 3. The results of the different life time predictions are presented in the same table as the relationship between the

Table 3. Results from the fatigue test and the life time predictions for bogie beam 1. The results are presented as N_f/N_p.

Method			S-N	LFM	LFM	LFM	HdM	HdM	HdM
Beam no	S_{max} (MPa)	Cycles 10^7		ΔK_{th} = 3.1	ΔK_{th} = 2.0	ΔK_{th} = 1.3	S_{op}= 0	S_{op}= 0.24	S_{op}= 0.43
VA 2	368	52.2	0.22	0.17	0.41	0.96	4.74	2.85	0.70
VA 4	368	>97.3 stop	-	-	-	-	-	-	-
VA 5	368	67.2	0.28	0.21	0.53	1.18	6.10	3.67	0.91
VA 12	368	62.4	0.26	0.20	0.50	1.14	5.67	3.41	0.84
VA 3	322	54.1	0.12	0.09	0.16	0.53	3.28	1.97	0.49
VA 6	322	90.4	0.21	0.15	0.38	0.89	5.48	3.29	0.82
VA 7	322	>179 stop	-	-	-	-	-	-	-
VA 8	322	107	0.28	0.34	0.45	1.05	6.48	3.90	0.97
VA 1	315	13.2	0.38	-	-	-	-	-	-
CA 9	226	14.0	-	-	-	-	-	-	-
CA 10	226	17.0	-	-	-	-	-	-	-
CA 11	226	25.0	-	-	-	-	-	-	-

Table 4. Results from fatigue tests and life time prediction of bogie beam 2. The results are presented as N_f/N_p.

Method			S-N	S-N	LFM	HdM	HdM	HdM
Bogie Beam	S_{max} (MPa)	Cycles 10^6	C = 0.45	C = 0.50	a = 2 mm	S_{op} = 0	S_{op} = 0.24	S_{op} = 0.5
1 PWT	275	3.26	0.41	0.33	0.36	35	22	3.26
2 PWT	275	3.98	0.50	0.40	0.44	43	27	3.98
3	275	4.81	0.60	0.48	0.53	52	33	4.81
4	275	5.13	0.64	0.51	0.57	56	35	5.13

PWT = Post weld treated

experimental value of the fatigue life and the calculated fatigue life, N_f/N_p. This is made for different threshold values and crack closure values.

In figure 5 the experimental results of the fatigue tests of bogie beam 1 are presented together with the results of the different life time predictions. The experimental results are presented as median values since that gives the possibility to use data also from interrupted tests with unbroken specimens. Life predictions made with different threshold values, ΔK_{th} = 3.1, 2.0 and 1.3, and with different crack closure stresses, S_{op} = 0, 0.24 and 0.43, are marked in the figure.

In figure 6 the life time for bogie beam 1 calculated with the modified HdM-method is presented as a function of the crack closure stress, S_{op}. It should be noted that using an S_{op}-value of 0 is equivalent to predicting fatigue life with the original HdM-method.

The experimental results from the fatigue tests of bogie beam 2 are presented in table 4. The results of the life time predictions made with the HdM-method, the S-N-method and the fracture mechanics method are shown in the same table. Life time calculations made with different values on the weld geometry factor, C, and the crack closure stress are presented in the table. The fracture mechanics calculation used an initial crack length of 2 mm.

In figure 7 the experimental results for bogie beam 2 are plotted together with the results of different life time predictions methods. When the S-N-method was used two different values of the weld category, C, was used, 45 and 50 respectively. Three different S_{op} values, 0, 0.24 and 0.5, were used for fatigue life calculations with the modified HdM-method.

In figure 8 the results of the fatigue life predictions made with the modified HdM-method for bogie beam 2 are presented for different values of S_{op} between 0 and 0.5 with a step of 0.05.

In figure 9 the influence of the slope in the S-N equation, β, on fatigue life is shown. The life predictions are made with the modified HdM-method for bogie beam 1, with S_{max} = 368 MPa and an S_{op}-value of 0.5.

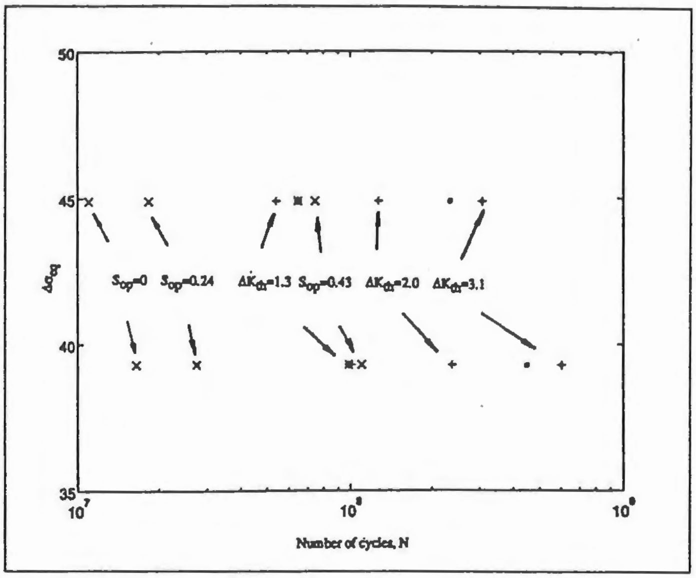

*Figure 5. The results of the fatigue tests and the life time predictions for bogie beam 1. × = predictions made with the HdM-method with S_{op} = 0, 0.24, 0.43 respectively, * = experimental result, median value ,• = life time predictions made with the S-N-method, + = life time predictions made with fracture mechanics method and with different threshold values, ΔK_{th} = 1.3, 2.0 and 3.1 respectively. It should be noted that the result at about 10^8 cycles contains both an × and an +.*

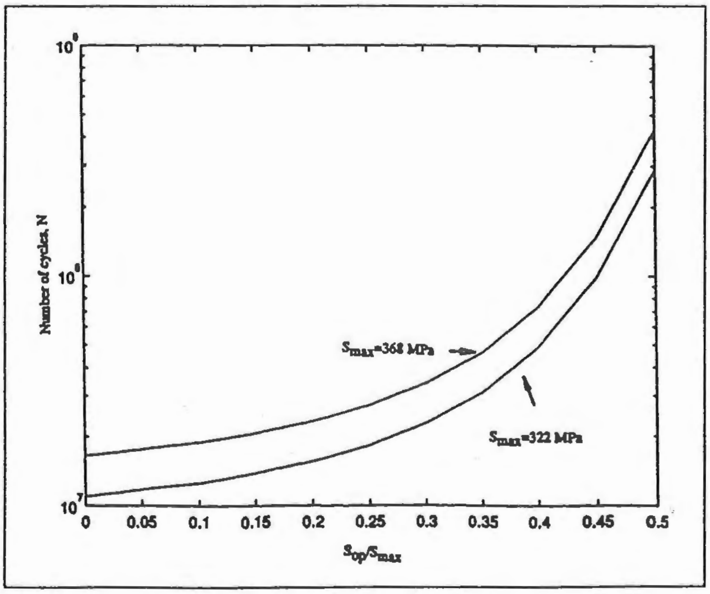

Figure 6. Life times for bogie beam 1 calculated with the modified HdM method as a function of the S_{op}-value used in the calculations. S_{max} = 368 MPa is equivalent with Δs_{eq} = 44.9 MPa and S_{max} = 322 MPa is equivalent with Δs_{eq} = 39.3 MPa.

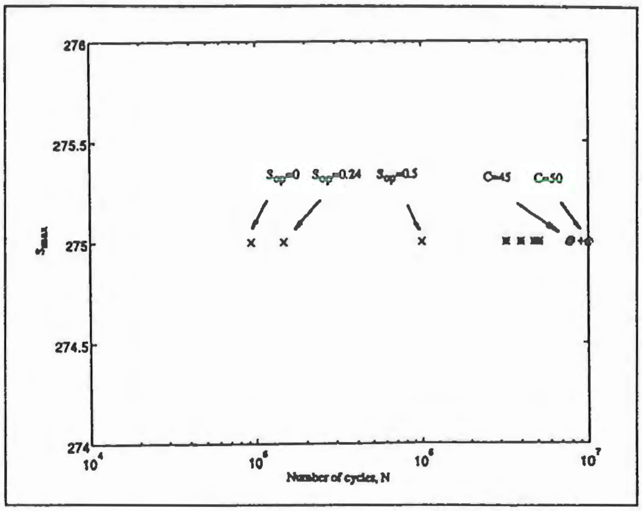

*Figure 7. The results of the fatigue tests and the life time calculations for bogie beam 2. × = life time predictions made with the HdM-method with S_{op} = 0, 0.24 and 0.5 respectively, * = experimental results, • = life time predictions made with S-N-method with C-values 45 and 50 respectively, + = life time prediction made with the fracture mechanics method and a initial crack length of 2 mm.*

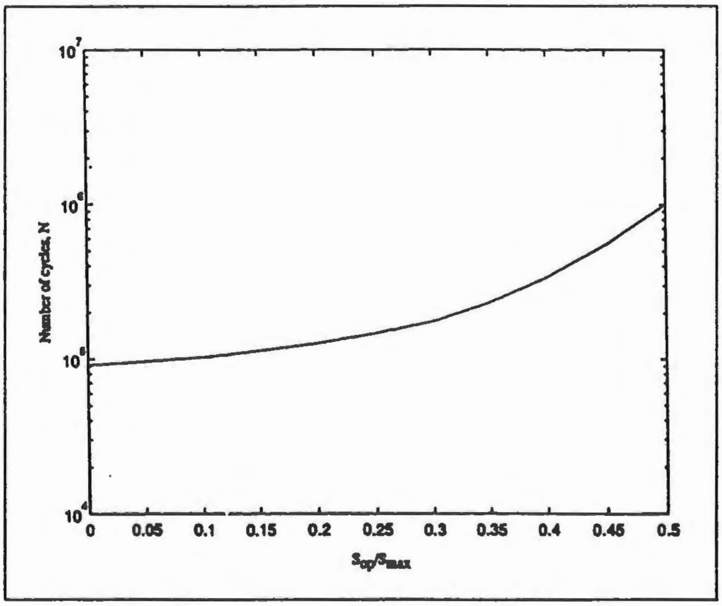

Figure 8. Life times for bogie beam 2 calculated with the modified HdM method as a function of the S_{op}-value used in the calculations.

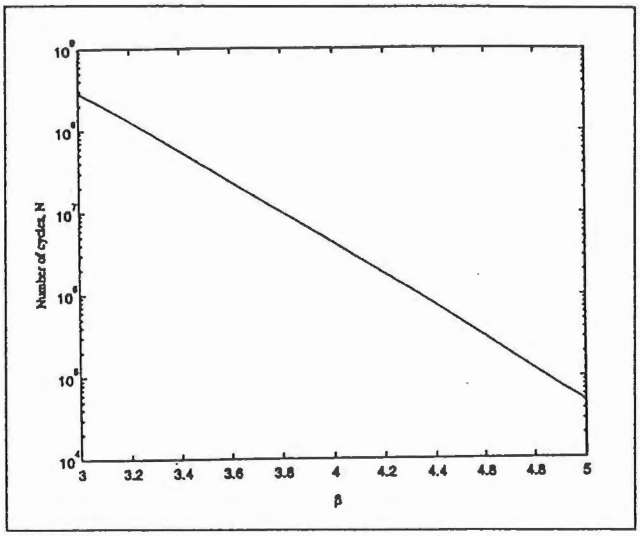

Figure 9. The fatigue life calculated with the modified HdM-method as a function of the β value. The calculations are made for bogie beam 1 and with S_{max} = 368 MPa and S_{ep} = 0.5.

DISCUSSION AND CONCLUSIONS

When the results of the life time predictions are compared with the fatigue test results it is clear that the HdM-method and its modification are more conservative than the S-N-method and the fracture mechanics method in most cases. In fact it seems as the HdM-method predicts the fatigue life in a conservative way for both types of bogie beams while the other two methods predict the fatigue life in an unconservative way. It is surprising that the life times predicted with different methods differ with as much as two orders of magnitude as in this study.

Both the S-N-method and the fracture mechanics method overestimated the fatigue life of both types of bogie beams. There are different ways to make predictions made with these methods more conservative, for example: use a low C-value in the S-N-method or by using low threshold values and long initial cracks in the fracture mechanics method. This was done in the life time calculations but even then the life time predictions were unconservative in most cases. A C-value of 45, a threshold value of 1.3 and an initial crack length of 2 mm are all rather extreme values. References [8-9] include rather long discussions about reasons why the traditional fatigue life prediction methods tend to overestimate the fatigue life of railway components. Therefore the rest of this discussion just deals with the HdM-method and comparisons with experimental results.

For bogie beams of the first type the difference between the experimental data and the fatigue life predictions made with the HdM-method is rather small, corresponding to between 1 and 5 times shorter fatigue life. For the bogie beams of the second type the differences are much bigger, as much as 50 times for $S_{up} = 0$. The reason for this is not fully understood but below some possible explanations are put forward.

There are some important differences between the tests of bogie beam 1 and bogie beam 2. The blocks in the load sequence used for testing of bogie beam 1 included 268.200 cycles while the bogie beams of the second type were tested with longer load sequences and the original load sequence included about 500.000 cycles. Also the irregularity factor differs between the two tests. Bogie beam 1 was tested with an irregularity factor close to 1 while bogie beam 2 was tested with a irregularity factor of 0.456. When the irregularity factor is close to 1, all load cycles have the same mean value, 184 MPa and 161 MPa for bogie beam 1, but when the irregularity factor is as low as 0.456 many small cycles will be superimposed upon the larger ones.

A rough estimation of the size of the plastic zone gives a radius of about 0.1-1 mm after the largest load used for testing of bogie beam 2. When this size is compared with fatigue crack data for bogie beam 2 reported in [17], and with the length of the load sequences used in the tests, it is clear that the crack had grown all the way through and beyond the plastic zone caused by the largest load before the load sequence was ended. This means that the S_{op}-value varied a lot during the crack growth in bogie beam 2. This was probably not the case for bogie beam 1 since the testing times were much longer for this type of bogie beams and therefore fatigue crack growth was much slower in this type of bogie beams. Also the lengths of the loading blocks in the tests of bogie beam 1 were shorter than the blocks used for testing of bogie beam 2. Finally the maximum stress in the block was larger for bogie beam 1 giving a larger plastic zone in bogie beam 1.

The influence of the S_{op}-value on predicted fatigue life is shown in figures 6 and 8. From the figure it is clear that the influence of the S_{op}-value on the life time is increasing with increasing S_{op}-value. It is therefore important to choose a correct S_{op}-value. In this study three different ways of estimating the S_{op}-value have been tried: the first way is to assume that there is no S_{op}-value. This is an extremely conservative way of estimating S_{op} and that is also supported by the experimental results. The second way is to say that only the largest load cycle in the load sequence influences the crack closure level. This is also a conservative way of estimating the S_{op}-value. The third way is to say that every load cycle in the load sequences gives a contribution to the crack closure and this is an unconservative way of estimating the S_{op}-value. The true S_{op}-value is probably somewhere between the second and third estimates.

In figure 9 the influence of the b-value used in the S-N-equation is shown. It is obvious that the influence of the β-value is great and therefore it is important to have a lot of experimental data when the β-value is calculated. In the same way it is clear from figure 6 and 8 that good approximations of S_{op} are needed.

The modified HdM-methods assumes that the S_{op}-value is constant during the fatigue life, or at least almost constant. This is not the case if the size of the plastic zone is small compared to the way the crack propagates during a load block and the load includes few large overloads. This is probably one of the reasons why the life time predictions made for bogie beam 2 became so conservative. In such situations a model with a variable S_{op}, such as the model presented in [18], is to prefer.

The S-N-curve used for life time calculations of bogie beam 2 was an estimation from a design curve. The accuracy of the estimation depends on several factors and for this special case very few of these were well known. Therefore it is reasonable to believe that the estimated S-N curve is uncertain.

The more traditional ways of predicting the fatigue life of bogie beams, the S-N-method and the fracture mechanics method, both seem to be somewhat unconservative, even when they were used with an initial crack as large as 2 mm or with a threshold value as low as 1.3. On the other hand the HdM-method seems to give lower fatigue life than the experimental data indicates. The possibility to use the HdM-method to find the lower fatigue limit in fatigue life predictions should be investigated further.

To conclude, the modified HdM-method may be used as a conservative way of predicting fatigue life of components, such as bogie beams, if the life times are long enough and the S_{op}-value can be approximated with a constant value; in other words if the fatigue crack growth during a load sequence is much smaller than the size of the plastic zone caused by the larger load cycles in the same load sequence. It is important to use accurate experimental data both for determining the equation for the S-N-curve and for the estimation of the S_{op}-value.

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