

FATIGUE DAMAGE ASSESSMENT OF THE GOLDEN HORN BRIDGE

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Abstract

Since the completion of the Golden Horn Bridge in 1974, the rapid traffic growth and increased truck weights have made the bridge vitally susceptible to fatigue damage. In this paper, the results of an experimental study to determine the remaining fatigue life of the bridge from the actual strain data induced by general mixed traffic loading over a 22 to 26 hour period, and also by two (slow and fast) test truck loadings are presented. Twenty-eight fatigue prone locations were instrumented with foil strain gages and the stress ranges were identified using rainflow cycle counting algorithm. The Palmgren-Miner linear damage accumulation rule, and stress range vs. number of cycles to fatigue data for certain details were used as the basis of fatigue life predictions. Generated amplitude spectra through the Fast Fourier Transform (FFT) technique was used to recognize behavior similarities or discrepancies of specified details.

Keywords: Fatigue Damage, Traffic Loading, Damage Accumulation, Steel Bridge

1 Introduction

Since its commissioning in 1974, the Golden Horn Bridge has borne the long distance traffic burden as a part of the E-5 road which connects Europe with Asia, as well as the larger volume traffic in the city area.

The length of the Golden Horn Bridge is 822.213 m for the steel bridge section and 153.362 m for the concrete bridge section. The steel bridge part consists of two eight-span continuous I-girders supporting the 31.2 m wide deck, including side walks. The total weight of the bridge is 6860 t. The height of the girders is 5.5 m. The bridge was fabricated in 1972 and erected in 1974.

According to the March 1990 Japan Consulting Institute report, the number of vehicles crossing the bridge is approximately 140 000 vehicles per day. The traffic volume crossing the bridge is about 5500 vehicles/hour at the peak, in one direction only. The future traffic demand forecast for the number of vehicles crossing the bridge is given to be 194.900/day in the year 2005, and the demand at the peak time is 15500 vehicles/hour.

With regard to the inspection results outlined in the March 1990 report, several number of cracks at critical locations were detected and recommendations for the repair

work were given. After six years, based on the recent inspection results this experimental study was found necessary for the reliable assessment of fatigue damage by direct measuring of stresses.

The results obtained from the field testing, Boğaziçi University Reports (1996 and 1997), formed the basis for the repair/retrofitting to be implemented by the General Directorate of Highways (KGM).

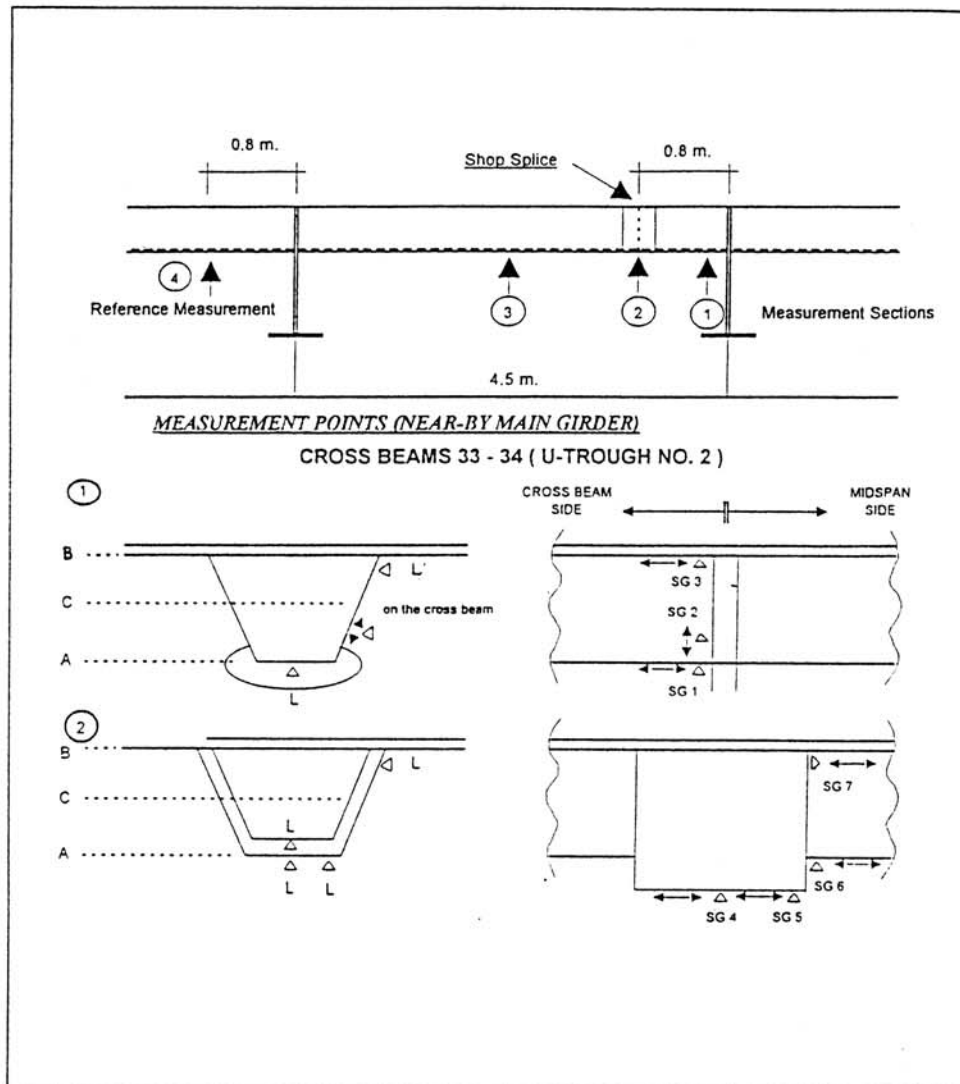


Figure 1. Locations of the installed gages 01-07.

2 Experimental Program

The field testing was conducted for the purpose of gathering the actual strain data recorded from the electrical resistance strain gages mounted at 28 critical locations that are selected based on the inspection results, some of which are shown in Figure 1. Data acquisition system was an HPE 1413A DVM&Mux.

Preliminary tests at laboratory conditions with probable noise effects performed with both 12.5 kHz cut-off and 100 Hz filters and also cut-off filter only, yielded good results. However, after the initial evaluations of the first long duration records made on site, it was found out that the grounding problems and persistent noise under field conditions could not be removed with cut-off filter only. As a result, additional 100 Hz hard filters are used during the tests. Thus, the strain measurements were carried out with the data acquisition system equipped to digital filters and recording seven mechanical strain measurements and one dummy gage to be used in temperature compensation.

2.1 Equipment

Foil type strain gages were used as strain sensors in the project. Because of the space constraints in locations for strain gage installations, the gage was chosen as small as possible. In this respect, 10 mm gage length was found to be appropriate.

Strain gages installed on the bridge deck were to be connected to the measuring device by cables. Since the distances from the gages to the strain measuring device reached 32 m for some locations, the cables should be properly shielded against the electrical noise in the environment and should have a very low internal resistance. The cable used consisted of stranded tinned multiwire copper conductors and semi-rigid PVC insulated and twisted pairs complying with DIN-47100 core identification standard. Before the installation, the internal resistance of each wire had been measured.

Strain gages were scanned and monitored by a data acquisition system with a built-in Hewlett-Packard computer running a software specially developed for this project. Sampling rate of this hardware setup is 100 Hz as required.

2.2 Loading & Data Processing

For test truck loading, a typical truck with the axle loads given in Table 1. was used. The truck passed along a given track first at a low and later at a high speed. In accordance with the location of the strain gages the truck passed either along the outer lane (Load Case 1) or outer lane (Load Case 2). The differences observed in stress levels due to speed increase are reported in Table 2 for a set of strain gages.

The data recorded during the slow-pass truck tests are gathered in Table 3. In this table a comparison with an available finite strip solution is also presented. Time series plots of both slow and fast pass results are produced and examples are given in Figure 2. From each channel a portion of the data around the peak signal was selected for the plots. Preliminary analysis of the time series confirmed the presence of noise in the vicinity of 50 Hz on all channels. The data was smoothed using a von Hann smoother, Hamming (1977), (a 3-point moving smoother with weights 0.25, 0.50, 0.25) which also has the effect of a low pass digital filter. The plots for all channels have been constructed after smoothing the respective time series.

Table 1. Test Truck Axle Loads.

Test Truck	Rear (tons)	Front (tons)	Total (tons)	Date of Testing
No. 1	16.0	4.6	20.6	03.04.1996 & 04.04.1996
No. 2	17.0	3.7	20.7	09.04.1996
No. 3	16.8	3.5	20.3	16.04.1996

Table 2. Test Truck Results of April 03, 1996. *Truck No. 1.*

Speed	Gage #	Stress in MPa		
		Max.	Min.	Range
Slow Pass 13.2 km/h Trough No. 2	01	1.34	-27.76	29.10
	02	2.29	-1.91	4.20
	03	4.21	-1.14	5.35
	04	0.96	-2.48	3.44
	05	7.36	-12.40	19.76
	06	27.72	-17.74	45.46
	07	0.57	-3.24	3.82
	Temp	-	-	-
Fast Pass 50.2 km/h Trough No. 2	01	1.34	-23.66	25.00
	02	1.53	-2.48	4.01
	03	3.25	-1.34	4.59
	04	0.29	-2.96	3.24
	05	7.46	-10.69	18.14
	06	21.21	-20.03	41.25
	07	-0.19	-3.43	3.24
	Temp	-	-	-

Table 3. Comparison of Stress Results for Test Vehicle Loading with Finite Strip Solutions. *Note the FStrip solutions are same for SG's # 4,5,6 and SG's # 18,19,20.*

Strain Gage	Finite Strip Results Stress in MPa			Test Results Stress in MPa			Load Case	Test Truck No.	Test/ FStrip
	Min.	Max.	Maximum Range	Min.	Max.	Maximum Range			
01	-28.98	3.21	32.19	-27.76	1.34	29.10	1	1	0.90
02	-	-	-	-1.91	2.29	4.20	1	1	-
03	-0.61	5.53	6.14	-1.14	4.21	5.35	1	1	0.87
04	-10.34	12.74	23.08	-2.48	0.96	3.44	1	1	0.15
05	-10.34	12.74	23.08	-12.40	7.36	19.76	1	1	0.86
06	-10.34	12.74	23.08	-17.74	27.72	45.46	1	1	1.97
07	-2.43	1.97	4.40	-3.24	0.57	3.82	1	1	0.87

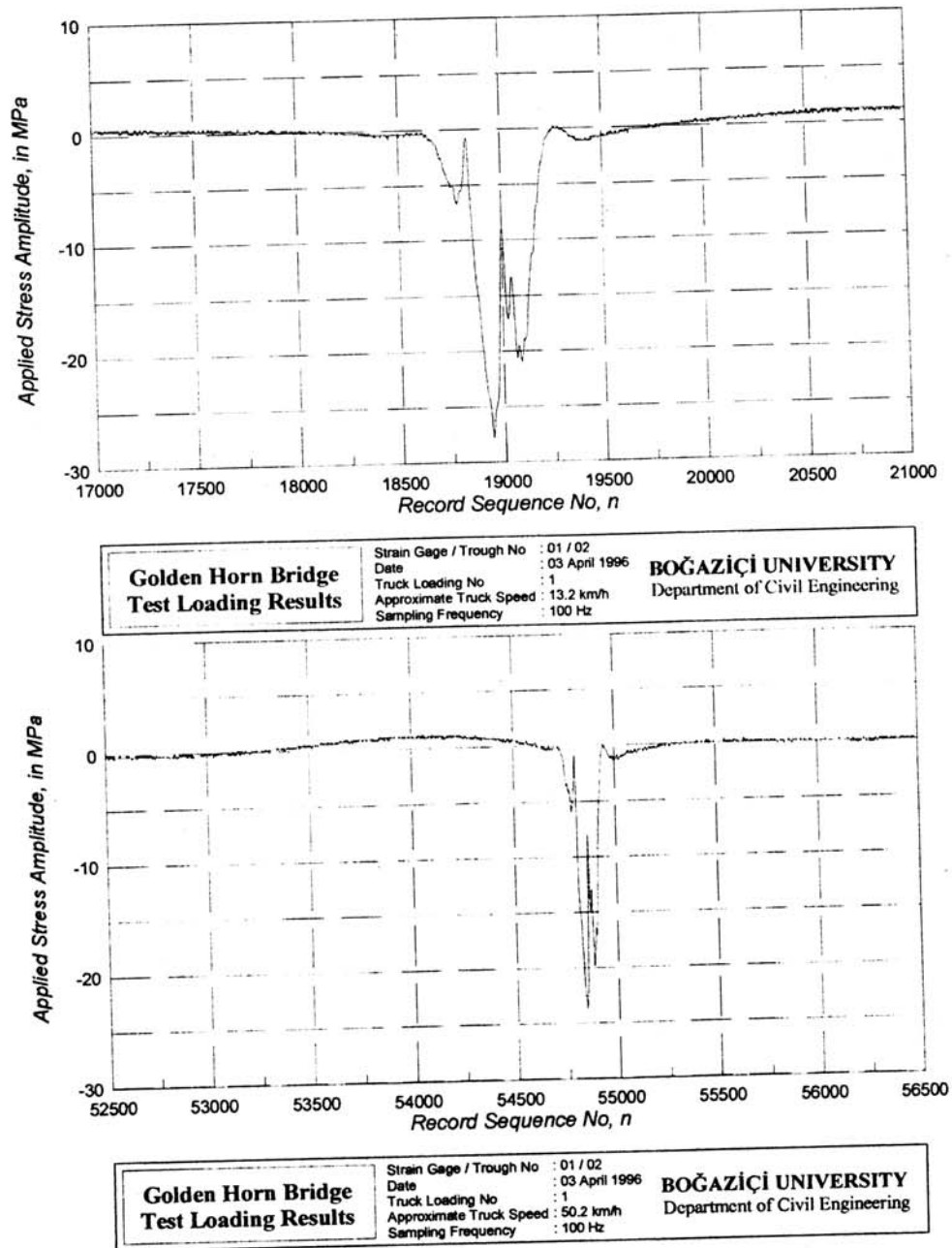


Figure 2. Example time-histories of truck test.

In the second phase after test truck loading, the data acquisition system continued to record daily traffic for 22 to 26 hour period for four days. The data acquisition system samples all connected channels at a rate of 100 Hz and records the data sequentially in a file. Periodically the current file is closed and backed up and a new file is opened for incoming data. This procedure led to the accumulation of 130-160 files during the course of a daily experiment.

At the end of the experiments, the recorded data were first transferred from the workstation environment (UNIX) to the PC environment (DOS). The measurements belonging to each gage were separated. Lead wire compensation and temperature correction were then applied to the data from each gage.

Prior to the fatigue life evaluation of the details, the data are examined whether the expected behavior is represented. For this matter, the reference was taken as the test truck measurements, that were already verified for their accuracy in the representation of the truck load history with the numerical results obtained using finite strip analysis.

All recordings were checked for errors, such as over-range records that are several orders of magnitude larger than the strain records, electrical noise due to the electronic and/or electrical instruments passing over or operating temporarily near the bridge, etc. and corrections were made as necessary. During the over-range and noise identification stages several pieces of the mechanical gage recordings are visualized and compared with the time histories recorded during the test truck loading.

To make an overall evaluation of the quality of the data, averages of the records are taken per 10 seconds and the fluctuations about the mean are observed. Knowing that the passing duration of a vehicle over a specified detail cannot be longer than a few 10 seconds, the fluctuations, about the mean, of the averaged data should be expected very low for the silent gages and still not significant for the heavily loaded locations.

3 Fatigue Strength Evaluation

For the fatigue life assessment of the details, British Standard, BS 5400 was employed. The standard assumes a life of 120 years to be spent until failure in order to accept a detail as of safe-life type. The calculated life spans give information on the quality and the condition of a particular detail in consideration. Therefore, the lives predicted for details which are classified according to this standard do not necessarily indicate that the time given as life span will be the time spent to the failure of the detail nor of the structure.

Using the Palmgren-Miner Rule along with the detail classifications and assigned fatigue resistance of these structural details, the life of a detail undergoing an irregular strain time-history was calculated. The theoretical life span of a structural element, in terms of the number of stress cycles which may be endured, depends essentially on:

1. the applied stress range $\Delta\sigma_r$,
2. the detail class which is applicable to the particular structural component or connection design.

In the following evaluations and computations, the general standards of workmanship and inspection, particularly with regard to the elimination of welding defects, are assumed to be moderate to high.

The safety verification is based on the application of the Palmgren-Miner linear cumulative damage rule, commonly called Miner's rule. The rule states that the damage from any particular stress range is directly proportional to the number of cycles applied at that stress. The damage after a number of cycles at different stress ranges are summed up to check whether a failure is expected. While applying Miner's rule, sufficient regularity of the daily loading process is assumed (ergodicity).

The influence of local stress concentrations, due to weld details and/or residual stresses, is implicitly included in the fatigue strength of the elements, evaluated according to the classes given in the standards Eurocode No. 3 and British Standard BS 5400.

3.1 Damage Accumulation

Structural details on which the strain gages were installed were classified with respect to the BS 5400. After this classification, the damage per cycle of a given stress range, $\Delta\sigma_r$, is computed using the following formula,

$$D_i = 1/N = \Delta\sigma_r^m / (K_o \times \Delta^d)$$

where,

- $\Delta\sigma_r$: Stress range (MPa),
- D_i : Damage accumulated per cycle application of a given stress range,
- N : Predicted number of cycles to failure of a stress range $\Delta\sigma_r$,
- K_o : A constant term relating to mean-line of the statistical analysis results,
- Δ : Reciprocal of the anti-log of the standard deviation of $\log N$,
- m : inverse slope of the mean-line $\log \Delta\sigma_r - \log N$ curve,
- d : number of standard deviations below the mean-line, taken as 2 for 2.3 % probability of failure.

and whose values, except the number of standard deviations, change for each detail class.

The damage for the complex strain history is formed using the list of stress ranges and number of half cycle counts obtained from the rainflow counting of these strain histories. The algorithm used similar to those as given in Murakami, ed., (1992).

The total damage, D_{tot} , was calculated from, $D_{tot} = \sum D_i \leq 1$.

Life of the structural detail under consideration under the given strain history is given as, $N_{detail} = 1 / D_{tot}$.

The results of these computations are summarized in Table 4. for each strain gage. In this table, the stress thresholds, ($\Delta\sigma_o$, non-propagating stress range), below which the life of a detail is assumed infinite, are also given for each gage. If there are no stress ranges in the recorded history that are higher than $\Delta\sigma_o$, infinite life is predicted. However, when the fluctuating stress with varying amplitude form a history, so that some of the stress ranges are greater and some less than this value, the larger stresses will cause the

enlargement of the initial defect. This gradual enlargement is reflected in the modification of the inverse slope, m , to $m+2$ as suggested by *EC 3* and *BS 5400*.

Table 4. Detail Classes of Structural Details at Gage Locations

Gage No	$\Delta\sigma_{r,max}$ (MPa)	Detail Class BS 5400	$\Delta\sigma_o$ (MPa)	Fatigue Life in Years	$\Delta\sigma_{r,max} / \Delta\sigma_o$
1	77	B	100.0	> 120	0.77
2	17, 19	D	53.0	> 120	0.34
3	24	F	40.0	> 120	0.60
4	9	G	29.0	> 120	0.31
5	59	G	29.0	88	2.03
6	104	G	29.0	4	3.59
7	27	G	29.0	> 120	0.93

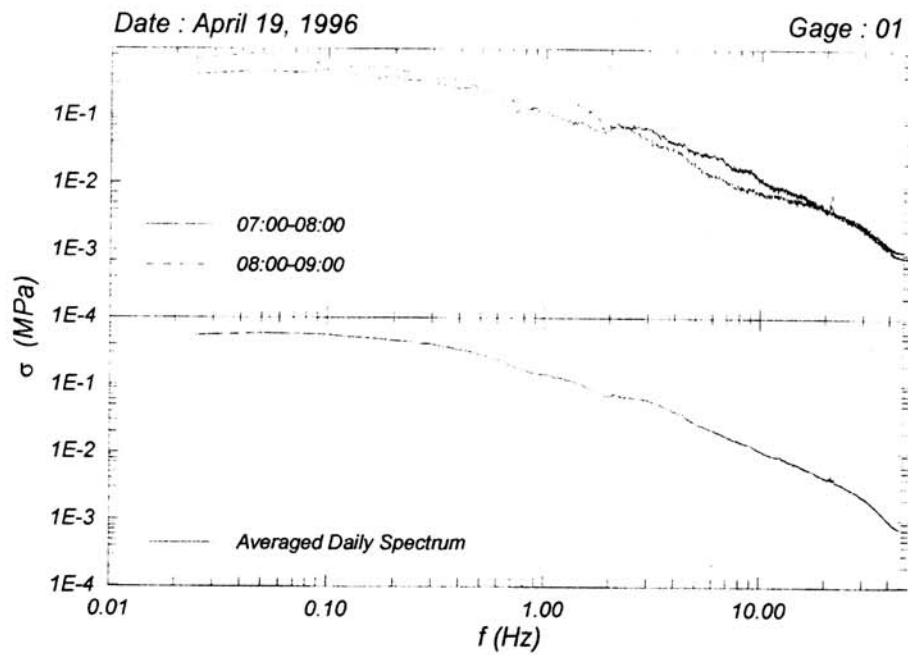


Figure 3. A set of sample outputs of spectrum analyses.

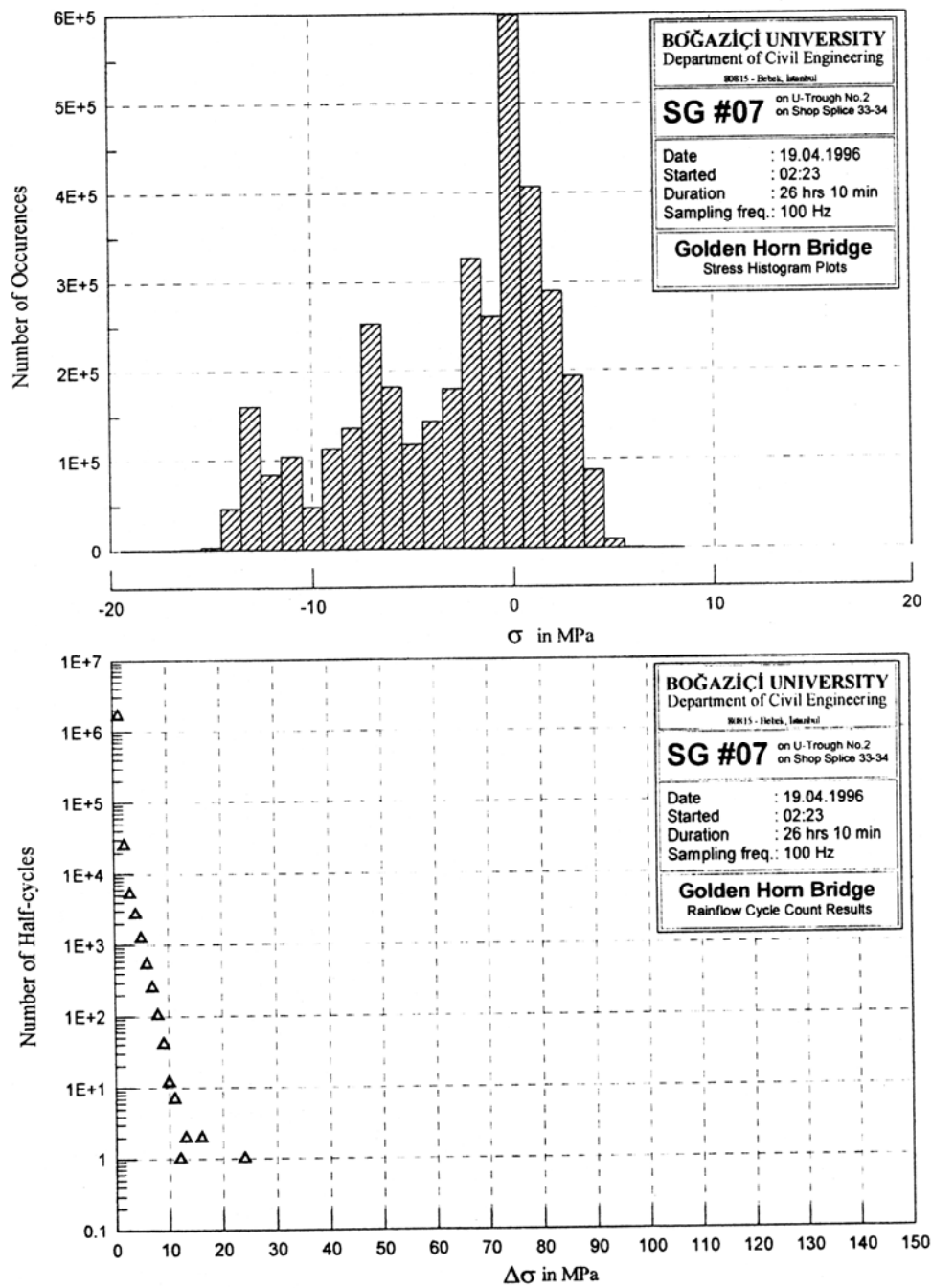


Figure 4. A set of sample outputs of rainflow analyses.

3.2 Data Analysis Using Fast Fourier Transform

Strain gage data were analyzed using the Fast Fourier Transform (FFT) to obtain amplitude spectra. Due to the large amount of data recorded during the course of the experiments, the analysis was carried out on an hourly basis. The stress amplitude spectra thus obtained were then combined to yield the daily spectra for the experiments.

During the preliminary analysis of the data, a spike, though small in amplitude, was found at a frequency of 50 Hz. This is thought to be the result of electric current detected on the body of the bridge. To remove the effects of this current and to improve the characteristics of the spectra, usage of the von Hann digital filter was decided upon.

The data for each gage was positioned in the time using the time stamps of the recorded files. The data until the beginning of the first full hour and after the last full hour of recording were skipped. Following segments of 360,000 data (one hour of recording at a rate of 100 Hz) were taken for analysis. Each segment was further divided into 88 segments and zero padded as necessary to yield sets of 4096 data. Each set of data was passed through von Hann filter and transformed to Fourier domain. To complete the analysis for one hour, the 88 sets were averaged at each frequency.

To obtain the daily stress amplitude spectra for a given gage, the hourly spectra at each frequency were averaged over the number of full hours comprising the daily record. As the peaks of the spectra are located in the vicinity of and below 1 Hz, the spectra were plotted using log-log axes. In general, the peak spectral amplitudes for all gages are on the order of magnitude of 0.1 MPa. The spectral peaks are in general located in the vicinity of 1 Hz or below 0.1 Hz.

A set of sample outputs of spectral analysis, Figure 3, and rainflow analysis, Figure 4, are provided.

4 Conclusion

The fatigue durability of the Golden Horn Bridge was estimated based on the analysis of the data obtained from the strain measurements. The analysis for the estimation of the fatigue life was based on the 22 to 24 hour recorded events in April 1996 under the general traffic loading.

British Standard, BS 5400 was used throughout this study. Linear damage accumulation, Palmgren-Miner rule, formed the basis of damage and fatigue life calculations. The stress ranges used in the calculations were identified using rainflow cycle counting algorithm.

The life predictions given in this study were computed assuming that the 24 hour samples repeat themselves throughout the given life of a certain detail. Therefore, the results must be interpreted in such a way that, if the given locations were of perfect condition and were subjected to the present live loading, the life would have been as given in the Table 4. However, special attention should also be given to the assumption that the effects of corrosion, thermal and surface imperfections were not accounted for. Hence, the most likely growth of the traffic flow over the forthcoming years and increasing truck weights when combined with the adverse factors mentioned above, may further reduce the fatigue lives given herein.

Within the scope of this work, the stress histograms, the amplitude spectra created using FFT and stress range plots obtained using rainflow cycle counting method were also provided to facilitate further studies and the interpretation of life predictions.

Amplitude spectra generated using Fast Fourier Transform were used to recognize similar patterns for identifying behavior similarities or discrepancies of the details. High frequency range (approximately between 40 to 50 Hz) was used as an indicator of presence or absence of noise. As evident from the very low amplitudes in the high frequency range, in all of the gage time-histories used in the analysis, no high amplitude noise was detected.

In this study, the performance of the selected details of the Golden Horn Bridge was evaluated under the increased truck weight and traffic volume. Due to these increases the quality of some details are found inadequate under the current increased stress ranges. These details are primarily located at shop splices and the improvement of the existing details to account for the increased stress levels are recommended.

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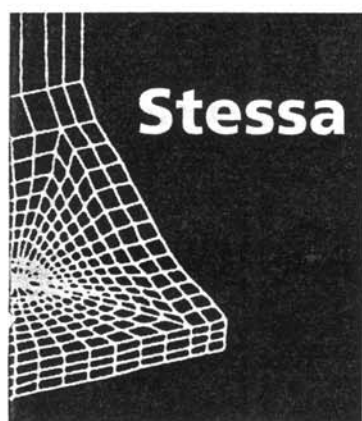
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