USE OF COMPUTERS IN THE DEVELOPMENT OF OFFSHORE RELATED LOAD HISTORIES

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ABSTRACT

For a long time metal fatigue was largely a descriptive subject. This has changed in the last four decades. The increasing power and sophistication of now ubiquitous desktop computers has meant an increase in the application of numerical methods, sometimes based on sophisticated mathematics, to fatigue research and development. Much current work on fatigue simply wouldn't be possible without computers. Fixed welded tubular steel platforms were first installed in the North Sea in 1966. They are subjected to significant fatigue loads due to wave action and a large number of fatigue tests have been carried out using standard load histories representative of service loads. Early load histories for offshore structures were based on theoretical calculation, from sea state data, of loads on tubular members. In 1983 a Common Load Sequence (COLOS), based on calculated load data, was proposed and it was implemented in 1985. COLOS has a return period of 5 million cycles and is made up from 7 different levels of narrow band random loading. Its development would not have been possible without extensive use of computer based numerical methods. Some of the background to COLOS is used as a case study on the importance of numerical methods in fatigue. It is a precursor to more sophisticated load histories which were developed later.

1 INTRODUCTION

For a long time metal fatigue was largely a descriptive subject (Pook [1]). This has changed in the last four decades. The increasing power and sophistication of now ubiquitous desktop computers has meant an increase in the application of numerical methods, sometimes based on sophisticated mathematics, to fatigue research and development. Much current work on fatigue simply wouldn't be possible without computers. In the Preface to his 1958 book 'Statistics of extremes', which includes fatigue applications, Gumbel [2] states 'Graphical procedures are preferred to tedious calculations.'. This is not surprising since at that time a typical desktop calculator was an electro-mechanical device which wouldn't even extract square roots automatically, and mainframe computers were in their infancy. In the 1960s programmable desktop calculators appeared and mainframes became more accessible: both started to be used for fatigue related calculations.

Fixed welded tubular steel platforms were first installed in the North Sea in 1966 (Pook [3]). They are subjected to significant fatigue loads due to wave action and a large number of fatigue tests have been carried out using standard load histories representative of service loads. Early load histories for offshore structures were based on theoretical calculation, from sea state data, of loads on tubular members. In 1983 a Common Load Sequence (COLOS) was proposed (Anon. [4]) and its implementation is described in Anon. [5]. Some of its background is used as a case study on the importance of numerical methods in fatigue. COLOS is a precursor to more sophisticated load histories which were developed later (Schütz and Pook [6], Pook and Dover [7]).

2..WAVE LOADING

Fatigue loads on tubular offshore structures derive mainly from wave action (Pook [8]). The primary parameter used in the characterisation of sea states is the wave height, H, which is measured from peak to trough. Over a period of time short enough (conventionally 20 minutes) for

Table 1. Scatter diagram for MV *Famita*.

$H_{1/3}$ (m)	Zero crossing wave period, T (s)									
	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
0.30	14	40	34	8	0	0	0	0	0	0
0.91	64	159	135	40	4	0	0	0	0	0
1.52	18	103	164	78	24	2	0	0	0	0
2.13	6	53	126	95	33	7	1	0	0	0
2.74	0	19	103	72	41	8	2	0	0	0
3.35	0	9	46	71	31	3	1	0	0	0
3.96	0	1	23	63	38	6	1	0	0	0
4.57	0	0	6	20	31	10	2	1	0	0
5.18	0	0	5	13	15	12	1	0	0	0
5.79	0	0	1	9	4	6	3	0	0	0
6.40	0	0	0	2	2	4	2	0	0	2
7.01	0	0	0	0	1	3	7	0	0	0
7.62	0	0	0	1	1	0	4	0	2	0
8.23	0	0	0	1	2	0	0	0	0	0
8.84	0	0	0	0	0	2	2	0	0	0
9.45	0	0	0	0	0	0	0	0	0	2

Parts per 1924

a sea state to be regarded as statistically stationary, the usual measurement of its severity is the significant wave height, $H_{1/3}$, which is the average height of the highest one-third portion of the waves. An available computer program was used by Holmes and Tickell [9, 10] to calculate wave loads, for various diameter members immersed to various depths, from sea state data collected on the MV *Famita* in the North Sea. They made two major simplifications in using the sea state data. Firstly, they assumed that the waves were unidirectional; in practice waves usually have a predominant direction. Secondly, the water surface elevation was assumed to be Gaussian and narrow band. This implies that wave heights follow the Rayleigh distribution and also that for a given sea state there is a predominant wave period. One of the ways in which wave height data can be usefully presented [8] is by means of a scatter diagram, which lists the relative occurrences of sea states within specified small intervals of $H_{1/3}$ and wave period, T. Table 1 shows the scatter diagram for the *Famita* data; the original Imperial units have been converted to SI units. There is a broad correlation between T and $H_{1/3}$, and as would be expected T tends to increase with $H_{1/3}$.

For a Rayleigh distribution the exceedance, that is the probability, $P(S/s)$, that a positive-going peak exceeds S/s is given by (Bendat and Piersol[11])

$$P\left(\frac{S}{s}\right)=\exp\left(\frac{-S^{2}}{2s^{2}}\right), \qquad (1)$$

where S is peak size (= $H/2$) and s is the root mean square (rms) value of the whole process from the (usually zero) mean value. Differentiating the exceedance gives the probability density.

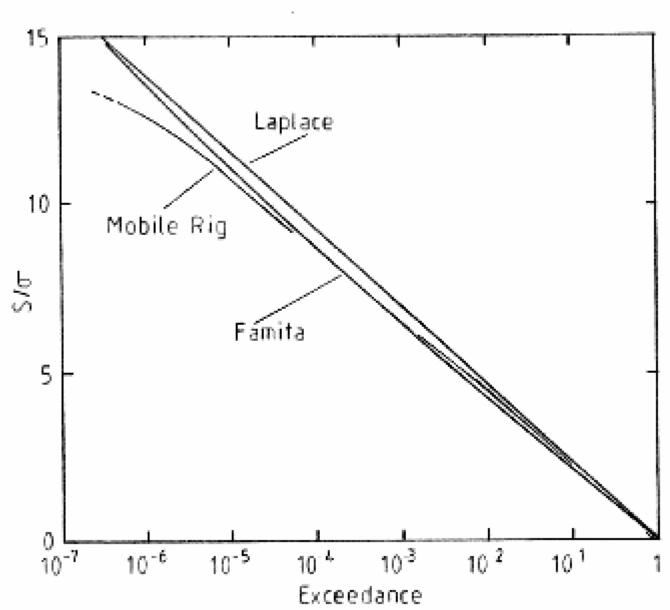

Figure 1. Wave exceedances for Famita (1.83 diameter member immersed 18.29 m) and Mobile Rig (2 m diameter member immersed 9 m) compared with the Laplace distribution.

Long term records show that the time history of $H_{1/3}$ has the appearance of a random process. Assume for the moment that all sea states are narrow band and their significant wave heights follow the (positive half) of a Gaussian distribution (Bendat and Piersol[11]), then

$$P\left(\frac{S}{s}\right)=\int_{S/s}^{\infty}\exp\left(\frac{-S^{2}}{2s^{2}}\right)\mathrm{d}\left(\frac{S}{s}\right), \tag{2}$$

where s is the rms of the Gaussian distribution. This integral does not have an elementary solution. If sea states follow the Gaussian distribution then if the wave period is constant it follows (Akaike and Swanson [12]) that the sum of the peaks follows the Laplace distribution

$$P\left(\frac{S}{s}\right)=\exp\left(\frac{-S}{s}\right), \tag{3}$$

where s is now the long term rms. It is a straight line when plotted on log-linear axes (fig 1).

Some data were examined (Pook [3]) to see whether the significant wave heights of sea states followed the Gaussian distribution, for example fig 2 shows sea state exceedances for a Mobile Rig moored on the Norwegian continental shelf. In the figure S/s values have been normalised so that they can be compared with the Gaussian distribution. The line shown was calculated from tabulated data representing a histogram of the sea-state probability density function. As this can be regarded as a continuous function the exceedances should appear as a continuous curve. The corner points on the line shown indicate upper and lower bounds to the curve. There is a deficit at

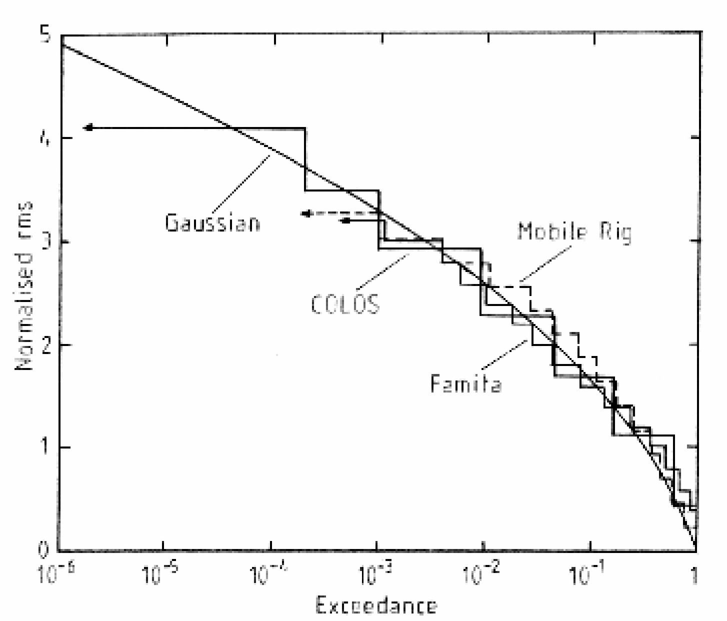

Figure 2. Sea state exceedances for Famita winter, Mobile Rig and Common Load Sequence (COLOS) compared with the Gaussian distribution.

very small levels and an excess at small and large levels. Clearly the distribution of sea states could not be regarded as Gaussian. It was later found (Pook and Dover [7]) that the sea state distribution was more accurately represented by the Gumbel distribution (Gumbel [13]). The sea state data for the Mobile Rig are well represented by the expression

$$P(H_{1/3}) = 1 - \exp\left[-\exp\left(\frac{1.9 - H_{1/3}}{1.06}\right)\right], \qquad (4)$$

where $P(H_{1/3})$ is the exceedance of $H_{1/3}$. It is well known that there are seasonal variations in the sea-state distribution, and fig. 2 shows *Famita* data for the winter six months only. Except at low levels the sea state distribution is close to Gaussian, but the full year *Famita* data (not shown) are not Gaussian.

Morison's equation, in conjunction with linear wave theory, shows that the force exerted by a passing wave on a large diameter member (larger than about 1½ m) is proportional to wave height, with some dependence on wave period, and decreases with depth of immersion (Morison et al [14]). Fig 1 shows exceedances for loads calculated from the *Famita* data for a 1.83 m diameter member immersed 18.29 m. The curve is concave upwards both because of the increase of wave period with significant wave height and also because the sea state distribution is not Gaussian. For a stiff structure, neglecting yielding, the stress (and strains) are proportional to the loads. However, this is not the case if structural resonances occur. Fixed offshore structures are therefore designed [15] so that resonant frequencies, in particular the fundamental (sway) frequency, are significantly greater than the wave-passing frequency. In practice, although sea states have a dominant frequency, they are not particularly narrow band, so energy may be available to excite resonances

Table 2. COLOS 7-level breakdown.

Level	Number of cycles	s/s_{overall}
7	1,000	4.07
6	4,000	3.46
5	40,000	2.90
4	180,000	2.27
3	575,000	1.68
2	1,250,000	1.10
1	2,950,000	0.426

at other frequencies.

Power spectral density (Bendat and Piersol [11]) (psd) plots provide information on the distribution of frequencies in a Gaussian random process. Bandwidth may be characterised by the spectral bandwidth, ε, which is a measure of the rms width of the psd and ranges from 0 (narrow band) to 1, and by the irregularity factor, I, which is the ratio of positive-going zero (mean) crossings, to positive going peaks. For a Gaussian process

$$e^2 + I^2 = 1. \tag{5}$$

A process is usually taken as narrow band if $I \geq 0.99$ corresponding to $\varepsilon \leq 0.14$. Power spectral density plots from strain-gauged offshore structures show a peak corresponding to the wave-passing frequency and subsidiary peaks at higher frequency corresponding to any structural resonances. When resonances occur the spectral bandwidth is substantially increased. The Mobile Rig is a stiff structure with strain gauges mounted on a 2 m diameter member immersed 9 m. There is a linear relationship between load and stress, with no resonances, so the stress/time histories are essentially narrow band. Exceedances are shown in fig 1. The drop off at high values of S/s is due to the effect of a finite sample size. The exceedance curve could well be represented by the Laplace distribution.

3 THE COMMON LOAD SEQUENCE

At a meeting held in 1983 (Anon. [5]) it was agreed that the Common Load Sequence (COLOS) should have a long term distribution based on the Laplace distribution with a return period (total number of cycles) of 5 million cycles. This was based on the observation, for example fig 1, that some calculated load distributions are close to the Laplace distribution. It was also agreed that COLOS should be built up from 7 stationary narrow band random processes of different rms levels. The Laplace distribution was broken down into the required 7 levels of Rayleigh distributions using what is essentially a trial and error graphical procedure (Pook [16]). However, in order to achieve accurate results trials have to be carried out numerically and a suite of specially written computer programs was used. The 7-level breakdown used for COLOS is shown in Table 2. Summing the Rayleigh distributions gives exceedances and probability densities within one per cent of the desired values for s/s_{overall} in the range 3.1 – 15.1 and within 2½ per cent in the range 2.1 – 15. 6 (Pook [17]). The validity of COLOS was confirmed when it was noticed that the Mobile Rig data (fig 1) were close to the Laplace distribution.

4 CONCLUSION

Fatigue testing using standard load histories is an important part of the fatigue assessment of engineering components and structures (Schütz [18]). The development of COLOS would not have been possible without extensive use of computer based numerical methods.

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