Fatigue vulnerability of jack-up platforms

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Mr C. A. Carlsen, *Det Norske Veritas*

The Paper highlights an important aspect of jack-up platforms, in particular with reference to the tendency for large jack-ups to be used in the harsh environment of the North Sea. To meet the criteria for yield and buckling within reasonable weights, the platform legs have been made of extra high strength steel (yield stress 690 N/mm²), thereby increasing the dynamic stresses. Fatigue in the operating mode has thereby become a governing criterion as fatigue resistance does not increase with yield stress.

52. The Paper does not discuss the transit mode. In practice this has proved to be the worst condition, particularly for wet tows.

53. In §6 it is stated that it is possible to miss the problem by using, for example, references 1 and 7 if the designer 'idealizes his loadings simply in terms of incidences'. In fact these documents call explicitly for a fatigue analysis.

54. With reference to §4, it should be mentioned that the actual natural frequency depends significantly on the foundation support conditions. This fact may be included for evaluation of a specific location, but at the design stage it would be more appropriate to use a pinned bottom support, and thereby obtain an upper limit of the natural period and hence dynamic amplification.

55. The curve in Fig. 3 is misleading because it neglects the leg interaction cancelling effects at small waves/short periods. Also the dynamic and static curves should approach each other at high periods.

56. The actual fatigue analysis in the Paper is an oversimplification which leads to misleading results (generally too short lives) because it neglects, for instance, short crested seas, directionality of waves, realistic jack-up damping which is 4–6% due to soil damping, and jacking system damping (see §32).

57. The actual life factor between the design curve lower 95% fractile and the upper 95% fractile is normally about 10 for the *S-N* curves in question, and not 5–50.

58. It is misleading to refer only to the effect of statistical uncertainties in the calculations. These must be added to the uncertainty of the *S-N* curve in giving the right effect, i.e.

$$U_n = \sqrt{U_{n_1}^2 + U_{n_2}^2 \dots}$$

where U_{n_1} is the uncertainty due to the *S-N* curve and U_{n_i} are the calculation uncertainties. The combined uncertainty would normally be given by the large uncertainty of the *S-N* curve U_{n_1} .

59. On the basis of the simple and uncalibrated analyses in the Paper, it should not be stated that the fatigue life of the platforms in the Gulf of Mexico is one year (§ 46).

Mr J. L. Dolan, *American Bureau of Shipping*

The Paper presents a good outline and procedure for estimating the dynamic effects on the fatigue life of a mobile jack-up drilling unit. However, the dynamic amplification factors and the associated reduction in fatigue lives are overestimated in the numerical examples given.

61. Fatigue life prediction is extremely sensitive to the selection of a number of influential parameters. When a conservative margin is applied to each of these parameters, the calculated fatigue lives can be underestimated by several times. The example given in the Paper appears to be the case.

62. The period of the fundamental frequency of the sample unit was first calculated as 5 s. However, a detailed calculation in part 3 of the Paper gives 3.8. Based on the set of Gulf of Mexico wave data given in the Paper, the number of waves in the height range of 2.4–3.7 m is reduced from 14 000 for a 5 s mean period to 6700 for a 4 s mean period. North Sea wave data show that the marginal probabilities of the wave period (summing the joint probability of all wave heights having this range of wave period) for the 5 s waves and the 3.8 waves are 0.2408 and 0.0095 in one location and 0.319 and 0.025 in a second location, respectively. The corresponding ratios of the probabilities are 25 and 13. In other words, the inaccuracy in the unit's natural frequency of this degree can easily lead to an underestimation or overestimation of the fatigue life by an order of magnitude.

63. In the detailed analysis, damping ratios of 5% and 2% were used in the deterministic and spectral approaches, respectively. The 2% of critical damping recommended by the American Petroleum Institute was meant for jacket structures. As the damping ratio is inversely proportional to the square root of the structure's stiffness for the same amount of physical damping, and because the stiffness of a jack-up is generally one order of magnitude smaller than that of a typical jacket structure, the 2% damping ratio would not be appropriate for a jack-up. In fact, some research workers advocate using a 4–10% damping ratio for a jack-up platform.

64. Also, due to the randomness of the sea, the resulting *DAF* reflected in the spectral approach would be much smaller than that of the maximum *DAF* obtained in the deterministic approach, using the same damping ratio. In fact, the *DAF* resulting from the spectral approach can be defined as the square root of the ratio of the variance of the response spectrum to the variance of the wave spectrum; the former can be calculated using the deterministic *DAF* as the transfer function. If a Bretschneider spectrum were assumed, the spectral *DAF* defined in this fashion would be given by

$$DAF(\text{spectral})^2 = \int_0^\infty \frac{5dx}{x^5 \exp(1.25/x^4)[(1-x^2)^2 + (2\xi x)^2]} \quad (23)$$

where $x = \omega/\omega_0$ and ω_0 is the resonance frequency, which is set equal to the modal frequency of the wave spectrum. Equation (23) can be approximated by

$$DAF(\text{spectral}) \simeq 0.785/\xi^{0.566} \quad (24)$$

For 5% critical damping, the deterministic *DAF* is 10 whereas the equivalent *DAF*

using the spectral approach is 4.33. Even if 2% of critical damping were used in the calculation, the *DAF* from a spectral analysis would be 7.22, which is still smaller than 10, which results from a deterministic approach. This trend is contrary to what is shown in part 3 of the Paper. the preceding estimate of the *DAF* is still on the conservative side. In a spectral analysis, only a small percentage of the wave spectra employed has its modal frequency coinciding with the resonance frequency. In addition, short-crestedness of the sea will give rise to further increase in the fatigue life.

65. Another source of conservatism in the Paper is the lack of consideration of fluid–structure interaction in the prediction of wave loads. Such a formulation usually requires an iterative scheme which is widely adopted in America in computer programs.

66. It may not be feasible to design, fabricate and maintain a structure completely free of flaws. Research workers now begin to deal with such situations adopting the system reliability analyses. The fatigue life of individual joints must be determined but their frequency of occurrence also plays an important role. In the example cited by Knapp and Stahl¹⁴ there were three joints that would fail within 50 years, 21 joints in 100 years, 41 joints in 200 years, and so on. The probabilities of having one joint fail in these groups of joints were determined to be 0.030, 0.071 and 0.071, respectively. In other words, with attention focused on the overall integrity of the structure, the most important failed joints need not be those possessing the least fatigue life.

67. It is agreed that the fatigue behaviour of jack-up platforms deserves greater attention than other types of offshore structure. However, in the Paper the case is overstated. Due to the random nature of the wave environment and uncertainties in the dynamic amplifications in fatigue damage, a simplified method with arbitrarily selected parameters for assessing fatigue lives of jack-up platforms is not advisable at present. Further studies and full-scale measurements are necessary for a better understanding of the impact of dynamic effect on fatigue lives of structures. Meanwhile it appears that the best measures to guard against fatigue failure in the design stage are attention to structural details to minimize stress concentration and fatigue analysis using the best available method for special cases.

Mr L. G. Ellis, *Department of Energy*

The third edition of reference 5 was published in 1984. This edition includes an amendment covering fatigue and omits the subsection in the 1977 edition which permitted a less rigorous analysis for mobile installations because of their greater ease of inspecting and repair. Thus all mobile installations including jack-ups now have to be designed to the basic *S–N* curve for tubular joints where applicable, and this is defined as the mean experimental data curve less two standard deviations, to provide an adequate factor of safety against fatigue failure.¹⁵

Dr Hambly

I am grateful to *Mr Carlsen* and *Mr Dolan* for their detailed comments which broaden the perspective on my Paper. It is helpful to examine the uncertainties involved in parts of the calculations.

70. On the question of how complicated should a proper fatigue calculation be I would consider a short calculation intrinsically more reliable than a very complicated analysis, if the essential factors have been considered. In practice both are

needed. But I would not consider simplicity a fault, and by aiming for a simple presentation in the Paper I have enabled others to understand what I have done and criticise it. I adopted the approach of the Paper several years ago when investigating the collapse of a platform. I first did a hand calculation in a few hours, and then over a period of months carried out a long series of deterministic and spectral analyses involving a considerable amount of computer calculation. The answers from the rigorous calculations were remarkably close to the initial hand calculation. In subsequent calculations I considered it sensible to develop the simple and the rigorous calculations in parallel, and necessary to understand the differences in their results as refinements and secondary effects were progressively included.

71. My comments in §6 about it being possible to miss the problem resulted from my having had access to a very detailed deterministic analysis, by an organization of international repute, which did miss the problem even though the method included all the steps of calculation listed in reference 6. The analysis considered a large number of stress blocks and the corresponding cycles for all the waves, but the blocks were based on representative combinations of wave height and averaged periods, without paying sufficient attention to the incidences of the various waves at/near the resonant period.

72. *Mr Carlsen* is right to draw attention to the problems of fatigue in the transit mode. I felt it wise to limit my remarks in §21 to a reference to my earlier paper¹⁰ on fatigue during ocean towage, because of my involvement as an expert in litigation relating to the subject.

73. Figure 3 was intended to be schematic; even so it was based on a dynamic modal analysis of the structure of the first worked example and it included the effects of leg interaction in small waves/short period. The diagram ignored the first harmonic resonance in the large 10-second waves, but even without this resonance one would expect the dynamic and static lines to differ by more than 30% in 10-second waves and by more than 10% in 15-second waves.

74. The analyses ignored the effects of short crested seas since there is little information generally available on the subject and on how it should be considered. Directionality of the waves was included as explained in §37 and §42. The figure of 25% of waves in §37 was based on fatigue studies similar to those in part 3 which took into account the power law relationship between fatigue damage and stress.

75. The statement in §14 that the actual life of a welded joint can be between 5 and 50 times the theoretical fatigue life was based on reference 2 Figs C2.5.3–2 and C2.5.3–4 which compare the X-curve with test results. There is a range of about 10-fold between the lower 95% fractile and the upper 95% fractile, as reported by *Mr Carlsen*, and a further factor of about 5 due to other influences. Slightly different ranges can be obtained by comparing other curves, such as the T-curve in reference 5 (1984 edition), with other data, such as reference 15.

76. The statement in §46 that 'the examples indicate theoretical service lives of the order of only one year' relates to the examples and was not intended to relate to all jack-ups. Many do have adequate fatigue resistance; but some do not. Even with a service life of one year a joint should not show signs of cracking until after about 10 years because of the factors discussed above and in §14, and the additional factor of 2 between theoretical fatigue life and service life mentioned in §37. None the less many cases of cracking have been observed within periods of exposure of less than 10 years.

77. *Mr Carlsen* and *Mr Dolan* are right to draw attention to the sensitivity of

the calculations to the damping ratio. It is unfortunate that this critical parameter frequently has to be based on assumption rather than offshore measurements. Measurements were made by Hattori *et al* (1982)¹⁶ by pulling units with tugs, releasing them and then measuring the logarithmic decrement of the ensuing motion. But it is not clear what the hydrodynamic damping will have been from the still water. Reference 7 uses these results; however reference 9 advises that during wave induced motion this damping is considered part of the forcing function, and if the structure moves at the wave frequency then the viscous damping is negligible. It is not clear in §63 why Mr Dolan should assume that the amount of physical damping should be the same for a jack-up as for a jacket while the stiffnesses differ by an order of magnitude. There is a need for a joint industry study to measure the ranges of values experienced on several types of jack-up on different seabeds with different sea and wind conditions.

78. The structures of the second worked example and Part 3 were mat supported units for which it was considered reasonable to use the recommendation of API RP2A, which was based on tests on jackets. The figure for damping is on the low side for the independent leg unit, and much higher damping might be appropriate for such a structure on a soft seabed. Although the chosen damping ratio in this case may be on the low side other assumptions may be unconservative. Stress concentration factors much larger than 3 exist in some welded joints, particularly those with gusset plates. Furthermore in small waves the motions of a resonating structure are sensitive to any stock in the guides and jacking systems; this can have a detrimental effect on dynamic motions in contrast to the beneficial effect of damping.

79. In §62 Mr Dolan is correct in pointing out the sensitivity of the calculations to the relationship between natural period of structure and the most common wave periods at the location. However he has confused the periods of my different examples. I apologise if this is not clear in the Paper. The first worked example related to an independent leg unit in 46 m (150 ft) water depth with natural period $T_n = 5.0$ s. The second worked example was a mat supported unit in 30 m (100 ft) water depth with $T_n = 4.0$ s. The structure in part 3 was a mat supported unit in 21 m (70 ft) water depth with its first three modal periods at 3.8, 3.8 and 4.2 s. The latter structure was small and designed for relatively small maximum waves in the Gulf of Mexico. Structures designed for North Sea conditions might be expected to be much larger with longer natural periods and be subjected to waves with longer periods.

80. Mr Dolan's comment in §64 on the reduction of the DAF in the spectral approach were borne out in the spectral analyses of Fig 6. In head seas with modal frequency coincident with the resonant frequency a DAF of about 7 was calculated with 2% critical damping. But that was the only direction of waves for which the structure behaved in a simple manner like a single degree of freedom system. For most wave directions and periods the calculated stresses were influenced by the interaction of the different sway and twisting modes which had different DAFs at any period, and by the spatial interaction of leg spacing and wavelength. As a consequence the resulting DAFs in the deterministic analysis were also generally below those of a single degree of freedom system.

81. It is true that only a small percentage of wave spectra has its modal frequency coinciding with the resonant frequency of the structure. However, fatigue damage is also caused by all the wave spectra with other modal frequencies which have significant energy at the resonant frequency of the structure.

DISCUSSION

82. Fluid structure interaction was ignored in the Paper because most of the calculated fatigue damage was caused by the large number of incidences of relatively small motions. In the deterministic calculation of Fig. 5 the most damaging block of waves of $2.1 \text{ m} \times 4\text{-seconds}$, caused leg motions in the water of the order of 0.005 m (single amplitude); i.e. about 5% of the water particle excursions.

References

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