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Review paper – a summary of the 1983-85 Cohesive Fatigue Programme

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INTRODUCTION

A crucial factor in the successful design of offshore structures, as in other industries where fatigue damage is possible, is the design of the structural details and joints. For offshore structures this includes both flat plate and tubular welded connections, made from structural steel, as well as threaded connections made from higher strength steels. Successful designing to contain fatigue damage in service requires relevant information on materials response and reliable techniques for predicting fatigue life of individual structural details. For offshore structures the problems of size, fabrication, quality control, environment and the nature of the loading need the endeavours of metallurgists, mechanical, structural and civil engineers to provide adequate answers. To meet this need the Science and Engineering Research Council (SERC)/Department of Energy (D.En) provided the resources for a multi-disciplinary University study and the papers presented at this conference represent the achievements in the last two years.

The 1983-85 Cohesive Fatigue Programme (CFP) has been under the general direction of a Steering Committee comprising representatives from the Offshore Industry, individual experts and University personnel. This committee closely monitored the progress of each project and in so doing became familiar with the work. Reporting of progress was done by each Investigator but given the close understanding of the work by Committee Members it was decided that it would be helpful if the main achievements from the programme could be summarised from the view of platform designers. This paper respresents such an attempt and it will be complemented at a later stage by a more complete account of the programme to be published as a separate HMSO document.

The subject divides fairly naturally into tubular and tether research work and these topics form the two main sections of the paper. The final summary shows how this work is continued in the new 1985-87 Cohesive Fatigue programme.

TUBULAR WELDED JOINTS

Introduction

The use of welded construction complicates the fatigue behaviour of tubular joints by building in localised stresses, changing the characteristics of the material and introducing defects in critical areas of joints. The environment within which these welded joints are used introduces the further complication of corrosion fatigue under random loading. The current fatigue design procedures are primarily based on the S-N approach using Miner's Rule to assess the fatigue endurance of details. This approach relies on the accurate prediction of the loading level and the stress concentrations and the availability of S-N curves appropriate to the level of stress analysis undertaken. Further it is assumed that the correct application of cathodic protection removes the problem of corrosion fatigue. The SERC/D.En programme has addressed some of the important fundamental areas associated with the fatigue design of structural details in offshore steel structures.

The tubular joint is the most common structural detail in offshore steel substructures and has already been the subject of extensive research over the last 10 to 15 years. The SERC/D.En programme includes a series of studies based on tubular joint details ranging from the residual stresses induced by welding to the prediction of crack propagation and the influence of the environment. Another area of the programme looks at stresses near weld toes. Three studies were included which are concerned with the design and fatigue behaviour of screw joint tethers typical of the details required for Tension Leg Platforms (TLPs). One other study considered candidate materials for line pipe.

This summary attempts to highlight the relevance of some of the results from this programme to current design practices. Results are not presented in detail and reference should be made to the individual papers to obtain the necessary data.

The Local Effects of Welding and Weld Geometry

The calculation of cumulative damage using the S-N approach relies on curves derived for different details which include the effects of welding and weld geometry. A comparison of the UK Department of Energy Guidance Notes and the American Petroleum Institute (API) recommended practice on fatigue design, highlights some of the areas where the treatment of data is inconsistent. The current D.En design guidance whilst recognising that post weld heat treatment affects the fatigue performance of a weld does not allow for any improvement currently due to the lack of sufficient data to quantify the effects of stress relieving. Similarly weld profiling improvements whilst encouraged have no quantifiable benefit although grinding to remove weld toe defects gives an increase in endurance by a factor of 2.2. The background document to the current issue of the D.En guidance concludes that "...weld profiling has not been found to be of significance when assessing the experimental data to be used as a basis for the revision of the current D.En Q curve". However, the API recommended practice presents two S-N curves to be used with and without weld profile. These are obviously areas where there is a lack of data as shown by the conflict in the codes. Many of the projects in 1983-85 SERC/D.En programme contribute data on this aspect and there are two projects directly related to providing a better understanding of these factors.

Residual Stresses

The project undertaken by Payne et al on residual stress caused by welding is a continuation of the earlier successful work which concentrated on circumferential butt welds in (straight) tubulars. The current phase now reported is concerned with the experimental assessment of residual stresses in welded tubular T-nodes. Theroetical work, although started in this phase, is not complete and continues in the current 1985-87 Cohesive Fatigue Programme. The reported phase consists of tests on three T-nodes (three Y-nodes are to be tested later), all with 915mm diameter chords and with varying brace dimensions, thicknesses and number of weld passes.

This phase was primarily experimental and several methods of measurement were used. Comparisons are shown between hole drilling and block sectioning techniques, both of which have been widely used for other applications but these comparisons were dissapointing as they show differences of 110 to 80 N/mm^2 between these two methods. Despite this it is considered that the block sectioning technique has given a guide to typical residual stress distributions. Ultimately there is a requirement to develop a non-destructive method of measuring residual stresses but this is beyond the scope of this project.

The conclusions of this phase must be regarded as tentative since insufficient work has been dome to clearly identify the trends in detail. The full benefits of this work will not be realised until an accurate theoretical model is developed when it will be possible to study the effects of various welding procedures and identify the governing parameters. The work is relevant to providing an understanding of the effects of welding procedures on residual stresses and the effects of subsequent stress relieving. Am important parameter in the assessment of existing defects is the residual stresses in the weld region. Without adequate methods of predicting or measuring these stresses, engineers are forced to make pessimistic assumptions.

Residual stresses can be affected by post weld heat treatment (PWHT), and in the tests undertaken by Dover et al, an improvement in fatigue life of nearly 30% was observed. This is based on the comparison of four 'Y' joints, two with/two without PWHT. Most of this increase in life was observed during the early crack growth period. This is an encouraging result since it confirms a predictable effect. However, it is not possible to measure the level of residual stress after PWHT non-destructively and therefore correlation of results is difficult. Earlier work using hole drilling on T-joints of similar size however (1) showed that PWHT could reduce the residual stresses from about yield to 0.5 yield. The effect could be more significant on larger joints where residual stresses could be at yield stress over a much larger volume. A greater effect on the residual stresses at the weld toe, and hence early crack growth, would also be expected from shot-peening which induces compressive residual stresses local to the material surface.

Having identified this benefit, a programme to investigate the effect of various treatments, such as PWHT, grinding shot and hammer peening, on early growth would be beneficial. Many other industries have used the manipulation of residual stress to great advantage in improving resistance to fatigue crack initiation. This possibility is as yet relatively unexplored for offshore structures.

Weld Size and Shape

The study of stresses near weld toes was part of the work undertaken by Elliot et al and is particularly relevant to current discussions on the codes of practice. Although the current UK design guidance incorporates a factor that accounts for thickness of the welded plate, based on perceived effects in tests, the reasons for this effect have not been fully quantified. One of the contributory factors is considered by many to be the weld shape and size which are also partially a function of the thickness.

Elliot investigated the notch stress concentration factor (SCF) which relates the absolute weld toe stress to the extrapolated geometric SCF at the weld toe. This effect is considered by current design procedures to be included in the S-N curve and hence notch stresses are not included in the stress analysis. Using the photoelastic method this study identifies relationships between the various weld toe parameters, the notch SCF and the geometric SCF.

The results show a sensitivity to several of the parameters studied and a range of useful results are presented. The most interesting results are those which show the effects of the weld size in terms of the leg length/thickness ratio. This has been found to affect both the notch SCF and the extrapolated geometric SCF. Increasing weld size increases the notch SCF and decreases the geometric SCF. For the weld shapes studied, the nett resultant local stress decreases with weld increase size. This overall effect would represent up to 25% reduction in the effective hot spot stress range over a typical range of leg lengths. To put this in perspective, the so called 'thickness effect' represents an effective hot spot stress increase of 35% over the range of thicknesses from 20mm to 100mm. This indicates that weld size effect is of a similar magnitude but opposite sense to the thickness effect and merits further attention.

A further question is raised by this result in relation to the use of geometric SCF as the basis for assessing hotspot stress and defining S-N curves. The current design methodology assumes that the notch effect is contained within the S-N curves determined from large scale tests on tubular joints and is independent of the geometric SCF. In this study the weld parameters have been shown to influence both the geometric SCF and the notch SCF in different ways. This implies that our current method of defining hotspot stress may not be accurate. Extrapolating to the weld toe from an area of linear stress results in SCF's that may include varying proportions of the notch SCF depending on the weld detail and the magnitude of the geometric stress concentration. This could be best resolved by determining the weld profile scaling that would permit designers to retain the use of geometric SCF's.

Further work on weld size was part of the study by Burdekin et al using thick shell and wedge elements. The use of the wedge element to represent the weld material is known to produce overstiff local behaviour, but, as the authors state, the modelling was not designed to give highly accurate and detailed stress distributions. The quantitative results of these studies must therefore be treated with caution particularly as the comparison with parametric equations shows more significant differences than would normally be expected. The trends do, however, show reducing 'hot spot' stress with increasing weld size.

Both the test programmes on tubular joints by Dover et al on Y, K and T joints attempted to measure some of the weld profile effects. In the tests on 'T' joints which included a number of weld geometries and quality of profile no observable correlation was possible. The results tend to confirm the conclusion from the UKOSRP I data contained in the background to the Department of Energy Guidance notes but the range of profiles was not as extensive as those considered by either Fessler or Burdekin

In the 'Y' and 'K' joint tests, attempts were also made to measure the notch SCF which was found to be varying from 0.9 to 3.0. Confidence in these results is low due to the difficulty of measuring the stresses and again no correlation of results is presented. The variation in notch SCF is more apparent in steel model measurements and presumably this is a contributory factor to the scatter observed in fatigue lives. Despite this a general change in notch SCF due to weld geometry is an important factor that needs to be determined and quantified in codes. This factor needs to be confirmed ultimately from steel model tests.

Whilst the current SERC programme has contributed to our knowledge on weld geometry and profiling, there are still a range of interacting effects that require further study.

Stress Analysis of Overlapped Joints

In current design practice using the S-N approach, the evaluation of the hot spot stress is based on a global analysis of the forces and moments in the primary structural elements. These are then used to calculate the fatigue performance of the structural details. The relationship between the global stresses and the hot spot stress in the detail is by stress concentration factors. Within the time and financial constraints of an offshore detail design project, it is not appropriate to undertake detailed study of more than a very small percentage of the joints on a structure. Designers therefore use approximate methods to evaluate SCF's and it has become the practice to use parametric equations such as those developed by either Wordsworth or Kuang. These equations have limitations and designers often find it necessary to extrapolate beyond the limits specified by the authors and to use the equations on other types of joint. The overlap joint is one such joint which is known to be very efficient for the transfer of loading between braces and is widely used in offshore structures. However, due to uncertainties about the SCF's, many overlap joints are penalised through the use of a general SCF, and in some locations, avoided.

The project undertaken by Dharmavasan et al studies the SCF's in overlapped K joints using acrylic models. The tests were undertaken on four joints with varying degrees of overlap in the g/D ratio range from 0.0 to -0.47. The results were used to derive SCF's at the weld toe for axial, in-plane bending and out-of-plane bending loadings on the braces. The results of the study were compared with the parametric equations of Efthymiou which were derived from finite element analysis and with Buitrago's equations for non-overlapped joints based on acrylic modelling.

The results showed that the highest SCF's occurred for the out-of-plane bending and unbalanced axial loading. This confirms the experience from design studies and of the known occurrences of failure in service. The comparison with the parametric equations is used to conclude that the Efthymiou equations are over-conservative and that Buitrago's equations are closer but have greater scatter and some are on the unconservative side. These conclusions should also note that the better agreement was with the equations derived from acrylic testing and that there are known differences between finite element analysis and acrylic modelling. Although no conclusions were drawn by the authors, the variation of SCF with degree of overlap is shown to be load type dependent but for many of the loadings typically experienced in primary bracing, the higher levels of overlap induce lower stresses. It is this dependence on degree of overlap which the Efthymiou equations appear not to model accurately for a joint of the geometry used in these tests. The Dharmavasan results are comprehensively presented in their conference paper and the reader is free to draw further conclusions of his own.

Crack Propagation Studies

The fatigue of tubular welded joints has several phases:

i) a crack initiation phase during which no detectable cracks exist;

ii) a period of micro-crack growth during which very minute defects (less than 1mm) begin to develop (probably at more than one site);

iii) a final crack-growth phase in which the crack grows to be through-thickness which is usually defined as failure.

a) In Air

From observation of these and earlier tests, the crack propagation phase can represent up to 90% of the life of the joints. It is therefore obvious that to improve our understanding of fatigue in welded tubular joints it is necessary to increase our understanding of the fracture mechanics. The study of fracture mechanics and the development of theoretical models is dependent on being able to conduct flat plate and tubular joint tests to provide the necessary measurements. The Cohesive Fatigue Programme included a series of projects which investigated aspects of fatigue crack growth.

Burdekin et al have carried out a series of tests on flat plates. Axial and bending loads were applied separately to a semi-elliptical surface crack in a flat plate. The results show differences between the two types of loading. The bending causes the crack to lengthen and hence the asepct ratio to increase. The axial loading results in a much lower aspect ratio. The authors conclude that the lives are significantly greater for the bending conditions.

Dover et al measured the crack growth in a series of tests on 'Y' and 'K' joints and compared the results with a number of theoretical models. They found that the prediction of early crack growth is dependent on the choice of a satisfactory weld toe notch SCF which, in turn, was difficult to measure. Models based on averaged stresses proved more accurate than results that used only the peak hot spot stress.

It is suggested that some form of stress distribution averaging is necessary if the fatigue life for various joint geometries is to be correlated more accurately. Whilst this is valid it is perhaps worth noting that joints with the better detail geometries, and hence lower stress concentrations, will tend to have a more even distribution of stress around the circumference.

Both Burdekin et al and Dover et al have successfully utilised weight function approaches to the determination of the stress intensity factor in an irregular stress field. This work is complemented by that of Brown et al using the line spring approach. This work shows that it is now possible to produce adequate values of the stress intensity factor for surface cracks and with the other semi-empirical approaches already available it is now practical for designers to use the fracture mechanics approach to predict fatigue life, remaining life or crack growth curves for simple tubular joints.

b) In Seawater

The corrosion fatigue data obtained from tests on tubular joints in this programme has shown that the application of cathodic protection at -850mV does not restore the fatigue life to that which would have been expected in air. Although a rigorous statistical analysis is not feasible this confirms the trends reported by other workers and tends to contradict the conclusions originally based upon the results of tests on plate cruciform type welded joints. Dover et al have also observed that not only is the crack shape affected by the presence of the seawater but that the crack growth rates observed during the final crack propagation phase of the tests on tubular joints is greater than would have been expected from the crack growth rates measured in air. Considering the uncertainty of the beneficial effect of cathodic protection and the allowance made for its application in the Department of Energy's revised Guidance Notes, it becomes increasingly important to relate the observations of trends from tubular joint tests to the data obtained from the more mechanistic experiments performed to study the effects of cathodic protection, crack tip electrochemistry and biological actions on fatigue crack initiation and growth. Crack growth data from test on tubular joints are vital to the prediction of these secondary influences on fatigue life. Before returning to these large scale fatigue results the material data will be reviewed.

The results obtained by Proctor et al show that at potentials lower than -800mV, X65 and X70 type pipeline steels exhibit a loss of ductility and the transgranular fracture produced during slow strain rate tensile tests is typical of that usually associated with hydrogen induced cleavage. It is expected that the additional work of this type being performed on a rolled quenched tempered structural steel with a minumum guaranteed yeild strength of 500MPa will demonstrate similar features illustrative of a possibly damaging effect of cathodic protection at normal levels of potential.

Fatigue crack growth rates have also been shown to be faster than those obtained in air when cathodic protection is applied, faster rates of growth being produced at the more negative potentials providing further strong evidence that the acceleration is caused by hydrogen embrittlement. The increase in growth rate at the more negative potentials is of a similar order to that observed by other researchers during corrosion fatigue crack growth tests on both pipeline and normal structural steels. At the free corrosion potential, intergranular fracture has been observed to occur throughout the stress intensity range whilst at potentials of -900mV and -1200mV up to 30% of the fracture surface exhibits cleavage fracture. It is observed that intergranular fracture has been reported by other workers to occur more frequently at stress intensity ranges below 20MPa$\sqrt{m}$ where at the free corrosion potential in particular, the restricted availability of hydrogen and the smaller reversed plastic zone size combine to enhance grain boundary separation, whilst at higher potentials and stress levels, transgranular cleavage fracture is encouraged.

Like earlier observations these results would suggest that the crack propagation rate in artifical seawater with an applied cathodic protection would be above that in air and would therefore be compatible with the reduction in fatigue life of tubular joints tentatively suggested by the data from Dover et al. The presence or absence of such an influence on fatigue life will however be dependent upon numerous other factors not considered in this project including the influence of the environment on crack initiation and the relationship between crack length and stress intensity factor in the joint configuration being tested.

Work on C Mn structural steels by Cowling et al has evaluated the influence of additives on the corrosion fatigue crack growth rate in NaCl at both anodic and cathodic potentials. At a cathodic potential of -1000mV a crack growth plateau was observed from tests in NaCl and NaCl plus Arsenate but reduced crack growth rates are observed in NaCl plus chloroplatinic acid. The latter is known to decrease the rate of hydrogen uptake, therefore these results confirm the increase in crack growth rate as a consequence of a mechanism involving hydrogen embrittlement.

Crack growth rates slightly above those determined in air however have been observed over a wide stress intensity range, ΔK, in environments that restricted the availability of hydrogen inclucing NaCl plus chloroplatinic acid at anodic potentials. It is proposed that crack growth enhancement could be produced as a result of anodic dissolution and reference is also made to the possibility that the environment may influence the reversed slip mechanism. The work completed and reported to date does not provide conclusive evidence to substantiate either mechanism to an adequate degree but it would seem that more than one mechanism is present.

These results however are compatible with the observations made in other parts of this SERC/D.En programme and support the general consensus that cathodic protection is likely to increase corrosion fatigue crack growth rates, as compared to air tests, by up to a factor of six over a limited stress intensity range due to the occurrance of hydrogen embrittlement. Under freely corroding conditions, where the effects of hydrogen embrittlement will be significantly reduced in structural steels with a yield strength of about 360MPA (e.g. BS4360 50D) and under the influence of anodic ploarisation, the slight increase in crack growth rates observed is unlikely to be caused by hydrogen embrittlement but could be associated with an interference with the basic slip mechanisms or anodic dissolution.

In other work by Hodgkiess the influence of environmental and loading variables on the electrochemical conditions at the tip of cracks in BS4360 Grade 50D steels was evaluated using a technique involving the placement of electrodes in the anticipated path of a propagating crack. Measurements recording the variation of potential and pH relative to both the bulk solution and the crack tip were made on unloaded specimens and on specimens subjected to a fatigue load. The effects of both anodic and cathodic polarisation and an epoxy based coating were also studied.

Some of the results obtained suggest a linkage between crack tip potential and pH but the causes of what are thought to be possibly important electrochemical transients are not apparent. Both unloaded and cyclically loaded specimens behaved in a similar manner when immersed in seawater under free-corrosion conditions. This behaviour showed that the high external potential recorded initially fell to a value close to the crack tip value after a short time, except when only very low cyclic forces were applied when a larger difference between bulk and crack tip potential was maintained. This observation has not been further evaluated.

The most significant factor to affect crack tip chemistry is clearly applied polarisation with both anodic and cathodic potentials being virtually as effective in changing the potential within the crack as upon the external surface. A cathodic potential has also been linked to a significant rise in crack tip pH.

In a project of closely related work by Cowling et al a series of tests on 25mm thickness three point bend fatigue tests were performed at 8°C on BS4360 Grade 50D steel to examine the influence of sulphate reducing bacteria (SRB) on corrosion fatigue crack growth behaviour. SRB cultures were from the lower Clyde Estuary. The main influence of these SRB is to produce H_2S which in turn inhibits the formation of molecular hydrogen from atomic hydrogen. The atomic hydrogen can be absorbed into the steel and this in return can accelerate crack growth rates. The SRB can also increase corrosion activity. H_2S concentrations of up to 300 ppm were achieved after 20 days exposure in these cultures.

Under constant amplitude loading, fatigue tests in ASTM seawater without SRB produced crack growth rates equivalent to those determined by many workers under essentially identical conditions thus confirming the adequacy of the experimental procedures though the addition of material appears to increase rates by a factor 2. Tests in 'live' seawater were carried out under cathodic protection conditions with a range H_2S levels from 10-130 ppm. The plateau growth rate at about 1.0-1.4 x 10^6 m/c were not sensitive to the sulphide concentration but gave a plateau growth rate of about 10 times faster than the -850mV ASTM solution. One feature of these high plateau growth rates is that at higher ΔK values the growth rate decreases after reaching the plateau as if the hydrogen entry cannot keep pace with the crack growth rate. An interrupted test re-established the plateau growth rate.

Crack growth rates in real structures must be less than those observed in laboratory tests because, the authors suggest, the probability of an SRB colony on top of a cracked welded toe is very low, the number of SRB in a surface is low and the growth of SRB would be inhibited by dissolved oxygen replenished by washing with bulk seawater. Nevertheless in some regions of offshore structures SRB activity could lead to H_2S concentrations of the order of several hundred ppm.

Following on from the constant amplitude testing, Cowling et al have conducted tests that attempt to simulate offshore service conditions using small scale laboratory specimens; that is corrosion fatigue in seawater containing SRB, cathodically protected under random loading (both filtered white noise and the C/12/20 spectrum). By segmenting the constant amplitude da/dN-ΔK curve predictions of variable amplitude behaviour were made assuming no sequence effects and the agreement is sufficiently good to provide a design upper bound. The authors note that although SRB are shown to enhance crack growth rates, further work is required to elucidate the mechanisms, particularly with respect to stop/start events in relation to the relevance of calms between storms.

These cycle by cycle estimates of damage show that simple modelling of seawater effects are possible and successful. The same was also true for the elementary crack prediction models used by Dover et al. However it must be remembered that in service the random loading is more complex and although interaction effects may be absent in these current tests the random sequence of sea states rather than cycles could produce more complex effects. Other features have emerged from the corrosion fatigue tests on tubular joints that still require explanation. These involve early and late crack growth. The early crack growth complication involved crack retardation possibly due to calcareous deposits, the late crack growth an unexpected acceleration in growth rate. Both of these factors require further study if the corrosion fatigue behaviour of tubulars is to be predicted.

It is well known that offshore cyclic loading is random in nature and a major feature of design of offshore structures involves collection and analysis (cycle counting) of load histories and prediction of fatigue life based on constant amplitude data. Hancock et al have addressed the former aspect by comparisons of cycle counting methods and the latter by comparing predictions based on CA data with crack growth information obtained under VA loading of various band widths. The crack growth data is presented in terms of the ΔK_h parameter which is a more correct representation than ΔK_{rms} and was previously used successfully at UCL for tests on tubular joints. The well known Miner's Rule assumes no stress interaction effects and can only work if the stress intensity is based on a n^{th} root of the n^{th} moment of the probability density function of a random sequence where n is the slope of the Paris Law or the negative inverse slope of the S-N curve.

The analysis work has shown that the cycles distribution information can be obtained from Rainflow Counting and in particular the n^{th} moment can be derived hence ΔK_h can be calculated. The assumption of no history effects implies that each half cycle gives the same increment of growth as it would under CA loading. However the experimental data shows that this is true for the narrowest band widths but progressively large band widths tend to rotate the Paris Law when expressed in terms of ΔK_h. This could be a consequence of stress history effects but may also be associated with growth rates in regions where the Paris Law does not apply (in this case near threshold).

From a design point of view, this work has confirmed the earlier work at UCL that assuming no interaction effects and using Rainflow counting to derive ΔK_h CA data could be used to predict random loading fatigue crack growth rates for band widths up to 0.67.

A further development in this work concerns the semi-theoretical prediction of ΔK_h. This solution, and an earlier one by Chaudhury et al [2], now make it possible to avoid lengthy rainflow counting techniques in assessing fatigue damage. The accuracy of these techniques are adequate for design purposes except where cycle by cycle damage accumulation measurement is necessary. Such detailed assessment is currently unnecessary and these new methods if adopted would represent a considerable economy.

Further work by Hancock et al described an analytical design method for predicting the distribution of crack lengths after a given number of cycles and the distributions of cycles to reach a given crack length starting from an initial crack size and growing it by fatigue under random loading. The results show that this simple method can be used to assess reliability of cracked components under random loading and a quantitative description of factors affecting reliability is given.

Equations for predicting the distribution of crack lengths and for predicting the distribution of cycles to achieve a crack length are presented and data derived from them are compared with Monte Carlo simulations and show excellent agreement for both narrow and broad band loading.

It would appear that Hancock et al do not use the most appropriate probability density function mentioned earlier in their analysis of broad band loading by Rainflow counting (see above). It would also seem that the calculation should be based on a random choice of growth rate within the scatter on measured growth rates, rather than taking fixed values and estimating upper and lower bounds, and that for the general case one would expect to be working from one distribution of crack sizes to a second distribution.

DESIGN AND ANALYSIS OF SCREWED TETHERS

Screwed mechanical joints have been commonly used for conductor components in offshore installations. The development of concepts like the TLP have put an additional demand on such joints, as their use in tethers makes them fundamental to the integrity of the structure and subject to much higher fatigue loading. Two SERC/D.En projects concerned with the design and analysis of tethers were undertaken in 1983-85 programme.

The study undertaken by Broadbent et al was a photoelastic and frozen stress experimental assessment of a proposed coupling. The coupling used standard thin-walled tubes with internal machined tapered-threads and a separate male connection. It is not clear from the project reports how this joint would be made and broken in the field.

The analysis of the photoelastic test results identifies that the critical regions are the thread contact and the root. The stresses in the contact region are affected by the quality of the surface finish and are localised. This is an area of study which can only be effectively addressed by testing because the surface finish and contact area are dependent on the details of the tooth shape. An understanding of the contact stresses becomes very important when they become of comparable magnitude to the local stresses at the thread root.

Stresses in the root, not surprisingly, can be reduced by increasing the fillet radius. The first and last threads, as would be expected, are the most highly loaded although an even distribution of load transfer was achieved over most of the thread. The stresses can also be reduced by increasing the pitch of threads. The data provided from the tests undertaken to date are useful in indicating controlling parameters and further iterations on the design are expected to reduce the maximum stress concentrations.

The project undertaken by Glinka et al concentrates on the development of theoretical analysis techniques for application to a screwed tether to determine the fatigue fracture behaviour of the thread. This theoretical approach was compared to the results obtained from a limited test programme. The tethers considered are of a more conventional thick-walled design with tapered threads. In order to determine the theoretical behaviour of the joint it was necessary to accurately predict the stress distribution within the connection. The authors have used a mixed finite element electrical analogue method to provide a cost effective method of assessing these stresses. The stress distribution in global terms was evaluated by analysing the coupling as a whole and then in detail by analysing a substructure on one tooth. The data from this detail assessment was then used with the electrical analogue model to determine the load distribution in the complete loaded coupling. This method could be used to redesign the local geometry of the thread without reanalysing the entire joint.

The high local stresses typical of threaded connection imply that the joint is likely to be subject to high strain fatigue loading and this has to be taken into account in the theoretical assessment of both the initiation of cracks and their subusequent propagation. Methods of analysis are proposed which include these effects. This project has not yet fully utilised the theoretical approach developed to study the parameters that influence the fatigue performance of this type of joint and only a limited comparison with test was possible. Further work needs to be done in order to validate the approach and to demonstrate its usefulness.

Both these studies on screwed tubular joints deal with a similar problem but the design of the joints is in each case very different. The merits of one design versus another cannot be evaluated unless additional factors such as the cost of manufacture and the ease-of-use in service are considered. Nevertheless, each study contributes data useful to the other. What appears to be missing particularly for the thin-walled tube project is an adequate specification of the objectives of the design being developed. This could be obtained from a consideration of typical load histories which would identify the level of stress concentrations acceptable.

The project by Jones et al concerned with higher strength steels for tension tethers sought to establish whether hdyrogen embrittlement could be identified during the testing of quenched and tempered alloy steels typical of those used for forged products. Tests were to be peformed on a 1.5 Ni Cr Mo Steel, a 3% Cr Mo Steel and a 3.5 Ni Cr mo V Steel, a version of the latter already having been supplied for the first North Sea tethered buoyant platform. An initial premise in this programme is that such steels will not be welded and the fatigue resistance of the component will be strongly linked to screw thread geometry and surface finish. It is further posulated that these higher strength quenched and tempered martensitic steels would be more susceptible to hydrogen embrittlement resulting from the application of cathodic protection at up to -1050mV.

In the work initially reported, the results of fatigue tests on smooth cylindrical specimens tested in air and seawater with cathodic protection have shown that failures have only been obtained at fatigue stress ranges approaching the yield stress, this being indicative of the beneficial influence of cathodic protection on the initiation of fatigue cracks. At the free corrosion potential however, particularly when conditions are favourable to enhance cervice corrosion, a significant reduction in fatigue resistance was observed for both the 1.5% Ni Cr Mo and 3% Cr Mo alloys.

Whilst the information obtained from this programme is of value in confirming that cathodic protection can be of significant benefit with respect to delaying crack initiation in a seawater environment, the work has not yet provided adequate information to establish whether these higher strength steels are more or less susceptible to he influence of hydrogen embrittlement under the application of high cathodic potentials as it is most likely that any such influence would be exhibited by pronounced increase of fatigue crack growth rate under given conditions and the possible change in the morphology of crack propagation. These points are to be addressed during further work.

The information available at the present time also suggests that the 3% Cr Mo steel is susceptible to cyclic softening, an observation which itself raises an interesting argument concerning the effects of cyclic plastic deformation on yield characteristics although it must be recognised that in practice such conditions will only occur within highly localised regions and thus be fully contained. Under these circumstances therefore, it is difficult to reach any conclusion concerning the relevance of cyclic stress strain behaviour of these higher strength steels on product performance without detailed analysis of stress strain histories.

SUMMARY

The papers in this Conference have demonstrated that significant advances in understanding of fatigue of Offshore Structurs has been achieved. This has led to the situation where design practice can be improved which in turn should mean lower maintenance costs during service.

Not all of the problems have been completely solved, however, and this has led to he start of new work in the 1985-87 Cohesive Fatigue Progamme. This new programme is including in particular:

a) the conjoint action of random loading and a seawater environment on fatigue crack growth in tubular and flat plate connections (also includes 'live' seawater tests);

b) further development of fracture mechanics solutions for tubular joints for simple and complex nodes;

c) studies of the behaviour of higher strength steels in a VA corrosion fatigue environment;

d) studies of novel joints such as threaded connections, extruded nodes, cast nodes and spherical nodes;

e) extension of the residual stress work to include Y joints;

f) studies of the influence of weld profile on the stress distribution and fatigue life to determine the reason for the 'size' effect.

As can be seen the proposed work has led naturally from the 1983-85 programme to embrace more complex environments and materials and a broader range of applications.

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