Fatigue strength of grouted tubular steel connections for offshore structures

Autor(en): **Billington, C.J. / Tebbett, I.E.**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **37 (1982)**

PDF erstellt am: **16.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-28963

Fatigue Strength of Grouted Tubular Steel Connections for Offshore Structures

Résistance à la fatigue des assemblages scellés au mortier de tubes en acier pour les structures "offshore"

Ermüdungsfestigkeit von mit Mörtel vergossenen Stahlrohrfüssen bei „Offshore"-Konstruktionen

C.J. BILLINGTON
Wimpey Laboratories Ltd.
Hayes, Middlesex, England

I.E. TEBBETT
Wimpey Laboratories Ltd.
Hayes, Middlesex, England

SUMMARY
Grouted connections form the primary structural connections between large steel jacket structures and their foundation piles and are essential to the integrity of the offshore installation. These connections are subjected to cyclic loading due to environmental conditions during grouting, curing and subsequent life. This paper describes and presents the results from tests simulating cyclic loading during early life and long term fatigue loading. Results include relationships of the S-N form and measured displacements. Implications for design and offshore construction are discussed and recommendations are made.

RESUME
Les scellements au mortier constituent les principales liaisons structurales entre les grandes structures en tubes minces et leurs piles de fondation, et sont essentiels pour l'intégrité d'une installation „offshore". Ces liaisons sont soumises à des charges cycliques dues aux conditions environnantes aussi bien durant l'opération de scellement que pendant la cure et la période d'utilisation postérieure. Cet article décrit et présente les résultats d'essais simulant des chargements cycliques à un âge jeune ainsi que les sollicitations de fatigue au cours du temps. Les résultats sont constitués de relations de la forme S-N et des déplacements mesurés. On discute des conséquences pour le dimensionnement des constructions „offshore" et des recommandations sont faites.

ZUSAMMENFASSUNG
Die wichtigsten Verbindungen zwischen der Stahlkonstruktion und den Fundationspfählen werden bei „Offshore"-Bauten mit Zementmörtel sichergestellt. Diese Verbindungen sind während des Vergiessens mit dem Mörtel, während der Erhärtung sowie während der Nutzungsdauer Wechselbelastungen ausgesetzt. Der Beitrag beschreibt die Resultate von dynamischen Versuchen, die die Belastungen im Anfangsstadium sowie die spätere Ermüdungsbelastung simulieren. Es werden die gemessenen Verschiebungen sowie Wöhlerkurven vorgestellt. Vorschläge für die Bemessung von „Offshore"-Konstruktionen werden unterbreitet und Folgerungen daraus abgeleitet.

1. INTRODUCTION

Cement grouted connections are used between large steel jacket structures and their foundation piles. Adequate static strength and long term integrity of these connections, which due to environmental conditions are subjected to continuous dynamic loading throughout their life, are essential. The UK Department of Energy has funded a comprehensive experimental programme at Wimpey Laboratories to generate design data for grouted connections. This paper presents the results of investigations into the behaviour of connections subjected to cyclic loads.

2. EARLY AGE CYCLIC LOADING TESTS

2.1 Objective

During grouting, relative axial displacements between the pile and sleeve can exist due to wave action, particularly for the first piles to be grouted. Reduced scale tests have investigated subsequent ultimate strength and performance. These tests were carried out at real time wave frequency.

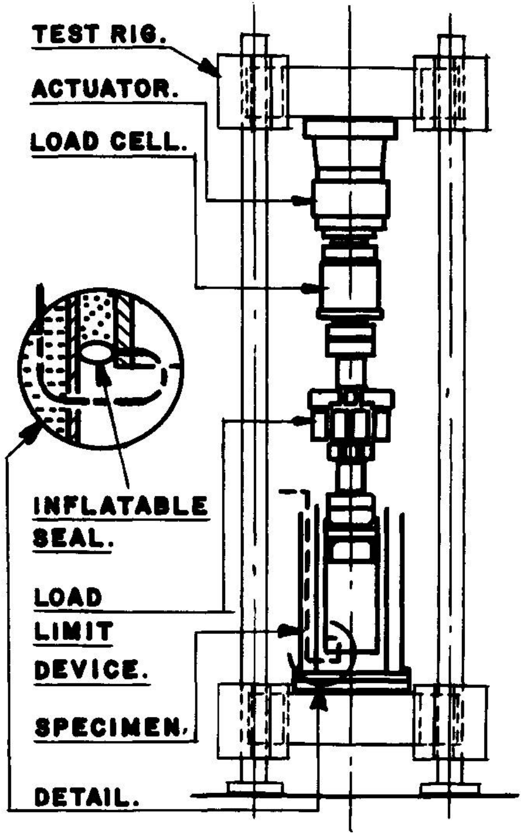

Fig. 1 Early age cyclic load arrangement

2.2 Details of programme

A total of eight tests were carried out using tubular geometries which represent approximately 1/5th scale of prototype connections on major North Sea installations. The grouted length (L) was equal to two pile diameters. Three specimens were plain pipe, the remainder having mechanical shear connectors in the form of weld beads. Two different cementitious grout mixes were used: an Oilwell 'B' mix in general use for structural grouting applications in the North Sea and a High Alumina Cement (HAC) mix which may be used when an early high strength is required.

2.3 Input displacement and load limits

The applied cyclic loading was designed to represent the effects of a 7.5 m wave on a typical jacket. For the example structure this produces a relative movement of $\pm$ 0.0035D before grouting or an equivalent bond stress of 0.06 N/mm^2 when the grout is set. The frequency of input was 0.1 Hz (approximate North Sea wave frequency) and a sinusoidal wave form was used. One test was carried out with input displacement of $\pm$ 0.0017D.

2.4 Test arrangements

The cyclic loading was applied by a servo hydraulic actuator within a stiff frame as shown in Figure 1. The actuator was operated in displacement control and an adjustable load limiting device was placed in series with the actuator. The input load was measured by load cell in series with the actuator and load limit device. Relative displacement of the tubulars was measured by independent transducers. Data from the load cells and displacement transducers were recorded on an X-time plotter.

2.5 Test procedure

The surfaces of specimens to be in contact with grout were shotblasted and the tubulars were then assembled concentrically. An inflatable rubber tube was used to effect a grout seal and tubular concentricity at the lower end. The specimen was placed in a cooling jacket and the whole assembly was placed in the test rig, as shown in Figure 1.

Water at 8°C representing North Sea temperatures was circulated through the cooling jacket. The cyclic movement was then introduced, the grout seal checked and the annulus filled with seawater. Grout was then injected into the bottom of the annulus displacing the seawater. Grout cubes were also cast and cured at 8°C for determination of grout compressive strength on completion of the test. Cycling was continued for a number of days after grouting with continuous monitoring of load and displacement. On completion, the specimen was subjected to ultimate load test using the procedures described in Reference 3.

2.6 Test results

2.6.1 Displacement and loads during curing

Typical displacement-time and load-time results are given in Figure 2. During the setting period the displacement reduces quickly with a corresponding increase in load. Thereafter the results indicate generally stable conditions, although some further reduction in displacement may occur. The shapes of the displacement and load cycles show very small elastic movements at the lower load range with larger rapid movements on or shortly after load reversal.

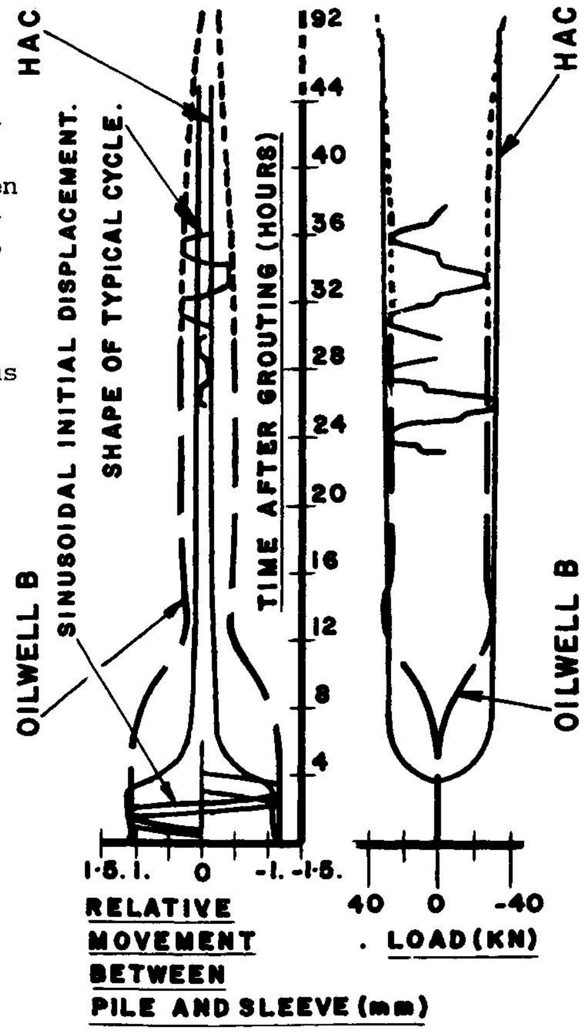

Fig. 2 Load-time and displacement-time graphs

2.6.2 Setting times & residual displacements

Initial set, as determined from the displacement-time graphs, occurred 3 hours after grouting for HAC specimens and 7 hours for Oilwell 'B' specimens. The HAC specimens reached a stable condition (minimum displacement, maximum load) by 8 hours after grouting, whereas Oilwell 'B' specimens did not reach this condition for approximately 24 hours.

All specimens exhibited a reduction in displacement during grout setting. However, displacements were not completely eliminated. Typical residual displacements were:-

Specimen type	Displacements as multiple of pile diameter	
	Input	Residual
Oilwell 'B' with shear connectors	± .0035	± .0003
Oilwell 'B' plain pipe	± .0035	± .0002
HAC with shear connectors	± .0035	± .0004
HAC plain pipe	± .0035	± .0018
Oilwell 'B' with shear connectors	± .0017	± .0001

For a ± 0.0035D input displacement it is found that residual displacements of the order of 10% of the input displacement occur except for HAC plain pipe specimens which exhibit much larger residual displacements (50%). This behaviour was not observed during some preliminary work carried out at approximately 1/20th scale and indicates that reduced scale tests may not fully represent prototype behaviour. For ± 0.0017D input displacement, very small residual displacements are recorded, these being comparable with typical elastic displacements.

2.6.3 Static strength after cycling

Plain pipe specimens gave average strengths 19% greater than predicted by the general formula (1) and specimens with shear connectors gave 10% greater strengths than predicted. Given the degree of scatter in the strength of grouted connections, these increases are not considered significant.

2.6.4 Stiffness during static loading tests

The general shape of the load-displacement curve was as expected. However the stiffness of the specimen and the displacement at which ultimate load was achieved were significantly greater than those recorded for comparable specimens not subjected to early age cyclic loading. Typical results are:

Specimen type	Displacement at ultimate load (mm)	
	Static only	After early age cycle
Oilwell 'B' with shear connectors	8	18
Oilwell 'B' plain pipe	18	45
HAC with shear connectors	8	15
HAC plain pipe	18	30

Similarly, at working load (one sixth of ultimate) the stiffness is significantly reduced by early age cycling.

3. FATIGUE TESTS

3.1 Objective

This programme was designed to investigate the performance of grouted connections under long term sinusoidal loading and to determine whether a relationship of the S-N form exists for such connections.

3.2 Details of programme

A total of thirteen specimens, including both plain pipe connections and connections with shear connectors, were tested. A single tubular geometry identical to that used for the early age investigation was used. To eliminate the effects of early age cycling and to enable the test on any one specimen to be carried out under near uniform grout compressive strength, specimens were prepared under zero load and cured for a minimum of 28 days at 8°C. In this case the grouted length of specimens with weld beads was restricted to give L/D = 1 because of load capacity limitations. Plain pipe specimens had L/D = 2.

3.3 Applied loading

Ten of the thirteen specimens were subjected to fully reversible sinusoidal loading at single amplitude. The magnitude of applied loads are expressed here as a proportion of the estimated ultimate strength of the connection (based on grout compressive strength determined from 76 mm cubes subjected to identical curing regime) and varied between ± 0.2 and ± 0.6 times ultimate strength. Initially tests were conducted at the extremes of this range to determine general trends in the results and establish the failure mechanism. High load tests giving short lives were carried out at 0.1 Hz and longer life tests at 3 Hz.

One specimen was subjected to unidirectional loading with zero minimum load and up to a maximum of + 0.8 times ultimate strength. Since failure of the grouted connection did not occur, this was subsequently tested under static conditions. Similar results were found for the plain pipe specimens under fully reversible load and these were also subsequently tested under static conditions.

3.4 Test arrangements

The cyclic loading was applied by a 1000 kN capacity servohydraulic actuator in a test arrangement similar (except with no load limit device) to that shown in Figure 1. The actuator was operated in force control with displacement and force responses monitored as load-deflection graphs on an X-Y plotter.

3.5 Specimen preparation

After shotblasting of surfaces to be in contact with the grout the tubulars were assembled concentrically on a timber and rubber base designed to seal the annulus and centralise the tubulars at the lower end. The specimen was placed in a large curing tank containing water at 8°C and the annulus filled with water. Grout was then injected from the lower end of the annulus displacing the seawater. Grout cubes were also prepared and cured in an identical environment; these were used to determine grout compressive strength at start and completion of the fatigue test.

3.6 Test results for specimens with shear connectors subjected to reversible loading

3.6.1 S-N relationships

For each specimen an estimate of the ultimate bond strength (f_{bue}) was calculated from measured grout compressive strengths and grouted lengths. The applied bond stress amplitude (f_{ba}) was also calculated.

The available test results are presented in S-log N form in Figure 3 in log S - Log N form in Figure 4.

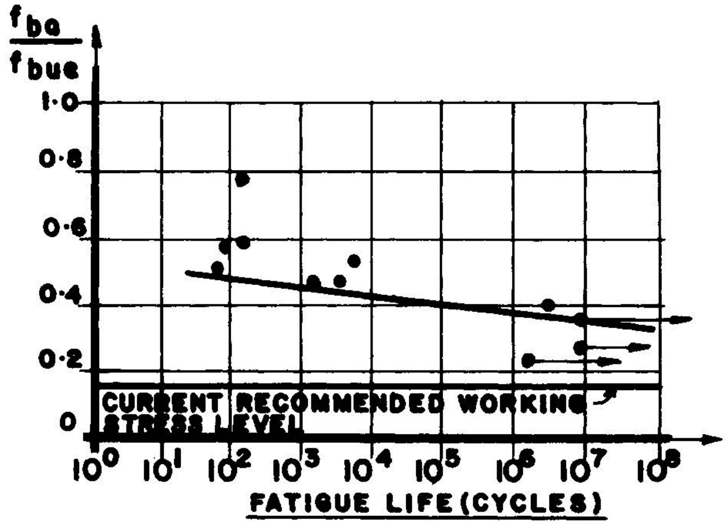

Fig. 3 Fatigue test results in S-log N form

The results form two groups: one group with lives in the range 10^1 to 10^4 cycles and the second group with lives in excess of 10^6 cycles. In the second group only one specimen actually failed, two others having been tested to 10^7 cycles without apparent deterioration.

The results indicate a value for f_{ba}/f_{bue} of 0.4 below which no failure occurs at less than 10^7 cycles (and possibly failure does not occur at all). Above

f_{ba}/f_{bue} of 0.4 a linear relationship has been found to describe the lower bound to the test results. Figures 3 and 4 also indicate the maximum permitted bond stress used in current design. This gives a safety factor of 6 on mean strength giving i.e f_{ba}/f_{bue}=0.166, which is less than half the identified endurance limit.

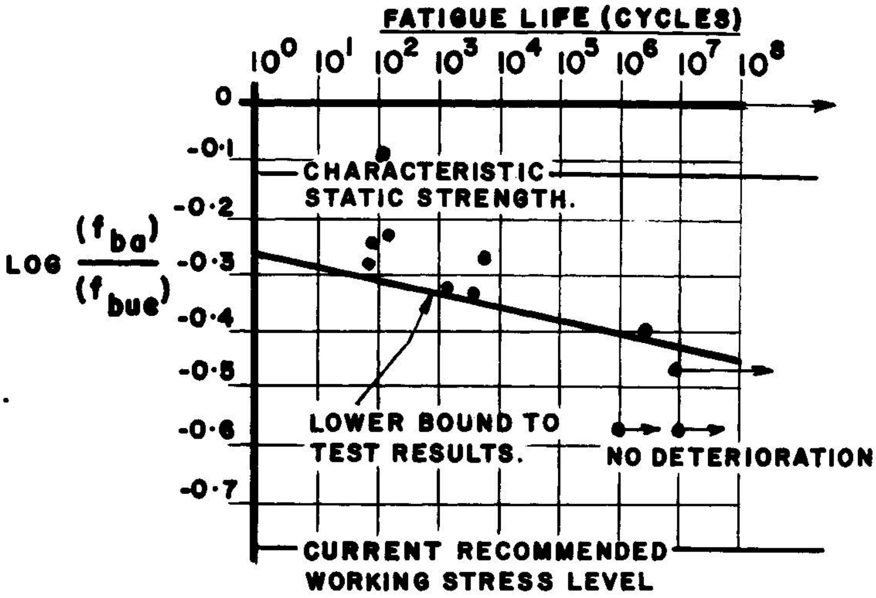

Fig. 4 Fatigue test results in log S - log N form

3.6.2 Measured displacements, hysteresis loops and form of failure

The connections failed by fatigue of the grout rather than of the steel tubulars. For specimens with f_{ba}/f_{bue} less than 0.4, a linear load-displacement is found throughout the applied load range with no measurable hysteresis loop. For more highly loaded specimens the maximum loads cause departure from the linear load-displacement relationships and since the load was fully reversible a significant hysteresis effect is present. A typical hysteresis plot showing the complete life for a specimen with approximately 80 cycle life is given in Figure 5.

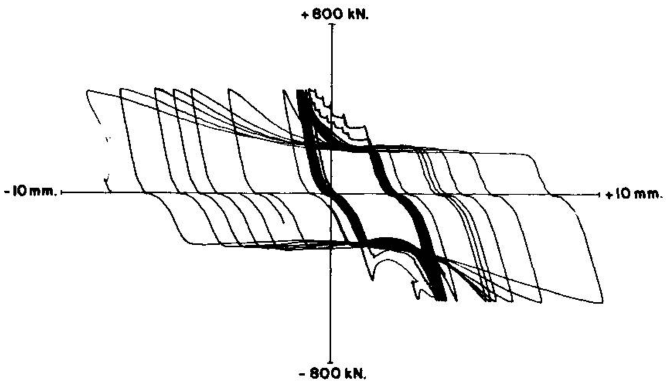

Fig. 5 Hysteresis of connection with mechanical shear connectors

When the measured displacement amplitudes for each cycle are plotted as shown in Figure 6, it can be seen that failure is sudden, with no loss of stiffness occurring before approximately the final five percent of the life. The form of failure of the more highly loaded specimens and the absence of any significant hysteresis effect when f_{ba}/f_{bue} is less than 0.4 can be understood by reference to the known failure mechanism under static loads (3). Only when the peak loads are sufficient to create a void adjacent to the weld bead can impact occur on load reversal leading to fatigue failure.

3.7 Test results for specimens with shear connectors subjected to unidirectional loading

One specimen with shear connectors was subjected to cyclic loading between zero and a maximum tensile load. This was initially subjected to approximately 10^6 cycles of load at cyclic stress varying between zero and 0.8 times estimated ultimate load without deterioration. A single large load well into the non-linear region was then applied. A further application of 2.8×10^6 cycles of fatigue loading was then applied without deterioration of the connection. The specimen was then subjected to ultimate load test to confirm the estimated bond strength.

The displacements under the single application of static load were sufficient to generate voids behind the shear connectors. However, since the load was not reversible impact effects did not occur and no further deterioration of the connection was recorded.

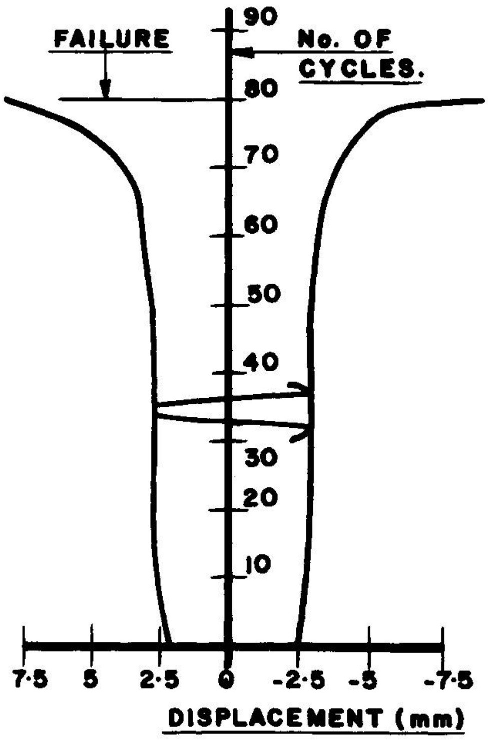

Fig. 6 Displacement amplitude against number of cycles for connection with mechanical shear connectors

3.8 Test results for plain pipe specimens

A programme of tests to determine an S-N relationship for plain pipe specimens was originally envisaged and three specimens were prepared for testing under reversible loading. The first specimen was subjected to a total of 10^5 cycles of load at 0.1 Hz over a range of maximum loads up to 0.5 times the estimated strength with no deterioration of the connection. The specimen was then subjected to 3×10^6 cycles of load at 3 Hz between 0 and 0.63 times estimated strength, again with no deterioration.

The mode of failure of a statically loaded plain pipe connection does not involve significant degradation of the grout such as that which occurs adjacent to a shear connector and it is generally found that the post ultimate strength of a plain connection is close to the original value until very large displacements have been introduced. The load-displacement characteristics of a plain pipe connection are also different in that failure is more sudden with very little non-linear behaviour before sudden slip of the connection. This and the results of the fatigue tests lead to the conclusion that fatigue of the grout was only likely to occur at very high bond stresses (perhaps greater than 0.8 times bond strength) and further testing was not undertaken in this programme. The two specimens already prepared were subjected to static loading to obtain improved estimates of ultimate strength.

4. CONCLUSIONS AND DESIGN IMPLICATIONS

4.1 Early age cyclic loading

(1) For the input displacements tested, the ultimate strength of a grouted connection subjected to cyclic movement during grouting and curing is comparable to that of specimens cured without movements.

(2) The test results indicate a significant reduction in stiffness both at working load and at ultimate load compared with specimens cured without movement. This has the following implications for design -

- unequal distribution of loads between piles in a group if the piles are not all grouted at the same time

- the designer may choose to limit environmental conditions in which grouting may proceed to keep displacements/applied loads to a level where significant residual displacements under cyclic load do not occur. Alternatively temporary mechanical devices could be used to restrict movements

- residual displacements may affect the long term fatigue performance

(3) Specimen size may influence test results and it is recommended that full scale tests are carried out to confirm the above conclusions.

4.2 Long term fatigue loading

(1) Grouted connections can fail by fatigue of the grout rather than of the steel tubulars. Failure is sudden with no loss of stiffness occurring until approximately the final five percent of life.

(2) An S-N relationship can be identified for grouted connections with mechanical shear connectors subjected to reversible loading.

(3) There would seem to be a stress range endurance limit (at approximately 0.4 times ultimate strength) below which failure does not occur and which has negligible influence on the life when subsequently subjected to higher stress ranges.

(4) Whilst the above endurance limit is greater than permissible stresses used in static design, fatigue has only been investigated for short connections (L/D = 2). In practice, connections are much longer (L/D between 8 and 16). Static design formulae are derived by factoring ultimate load which, because of the inherent ductility, occurs after complete redistribution of elastic peak stresses. Situations may arise where elastic peak stresses lead to local fatigue failure; the residual capacity and capacity for redistribution would be low and progressive failure might result. Further testing of longer specimens is required.

(5) Plain pipe connections and connections subject to unidirectional loads are less susceptible to fatigue failure than connections with shear connectors subjected to reversible loading.

(6) The interaction of early age cyclic loading (during grouting and curing) and long term fatigue loading has not been investigated. The effect of impact due to the presence of voids adjacent to weld beads is such that the subsequent fatigue performance of connections subjected to reversible loading may be affected by early age cyclic loading and this requires further investigation.

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