KAWASAKI STEEL TECHNICAL REPORT
No.22 (May 1990)
Advanced Technologies of Iron and Steel,
Commemorating the 20th Anniversary
of the Technical Research Division

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The principal feature of the premium threaded connection "FOX" is the introduction of a pitch change concept to the thread design. The thread has three different pitch areas. One area in the center is of identical pitch, and the others are of increasing clearance between loading flanks towards both ends in the hand tight state. Hence, the extremely high level of contact pressure, which is inevitably caused on the loading flanks of the end threads in the conventional thread design, is significantly reduced, and the central perfect threaded area shares loads, thereby realizing a more even load distribution in both the mode-up and the tensile loaded states. Finite element analysis (FEA) and a micro computer were effectively combined in the development of the FOX design. FEA shows that the FOX connection has good advantages, such as anti-galling property, leak resistance, and improved joint strength, because of the even contact pressure distribution along the threads. The pitch change criteria were discussed by varying the amount of pitch change in the FEA models, and the current design was proven to be best among those in the trials.

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Stress Analysis of Premium Threaded Connection "FOX" by Finite Element Method*

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1 Introduction

API (American Petroleum Institute) threads have been widely used as the standard connections for oil country tubular goods. However, the gradual depletion of easily obtainable natural resources and the advance of exploration technology have encouraged challenges to exploit severe wells. Since such wells are deep and contain corrosive or toxic gases, such as hydrogen sulfide, at high temperatures and high pressures, they require more reliable connections of sophisticated design, like the premium threaded connection.

In 1983, Kawasaki Steel Corporation started a joint development of the premium threaded connection "FOX" with Hunting Oilfield Services Limited (UK) and completed it in 1985.

Since the initial design verification test, all subsequent tests have shown that the FOX connection has fully satisfied every important requirement for the premium connection, such as anti-galling property, gas leak resistance, and joint strength.

In this paper, the FEA procedure, which was useful for assisting in the design of the FOX connection, is introduced, and the results are verified by comparing them with experimental data. Furthermore, the effect of the pitch change on the stress distribution in the connection was studied by varying the amount of pitch change in the FEA models.

2 Features of the FOX Connection

The features of the FOX connection are illustrated in **Fig. 1**, and are summarized as follows:

(1) The pitch change concept is applied[1].

* Originally published in *Kawasaki Steel Giho*, **20**(1989)3, pp. 202-207

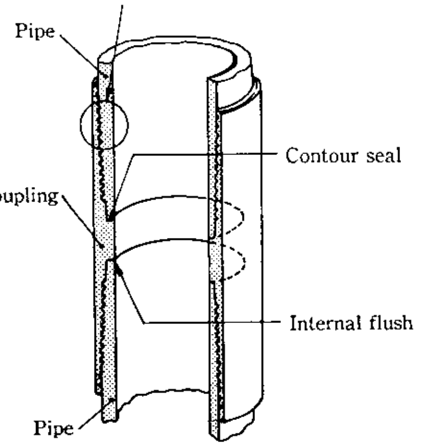

Fig. 1 Features of FOX connection

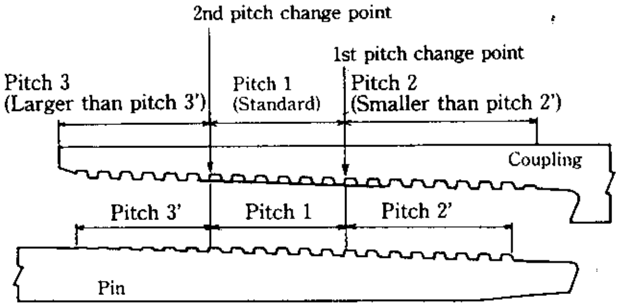

Fig. 2 Pitch change sytle in FOX connection

(2) The triple radii seal with three blended arcs (contour seal) is introduced in both pin and coupling. This not only achieves excellent seal effect but also makes the connection highly resistant to over-torque[2]. This design works to reduce stress concentration during make-up and compressive loading.

The principal feature of the FOX connection is the introduction of the pitch change concept to the thread design[3]. This is a unique concept which was first used in premium threaded connections.

The application of the pitch change concept to the FOX connection is shown in **Fig. 2**. There are three different pitch areas, when pin and coupling are mated. The pitch of the pin thread is larger than that of the coupling thread at the pin end, and is smaller at the coupling end. The pitches of both pin and coupling are identical in the middle portion. The objective of this concept is to control the amount of clearance between the loading flanks of pin and coupling, created by their different pitches.

Figure 3 gives an example of contact pressure distributions on the loading flanks in made-up connections, with and without the pitch change concept. The conventional threaded connection (broken line), without pitch change, generates peak contact pressure at the

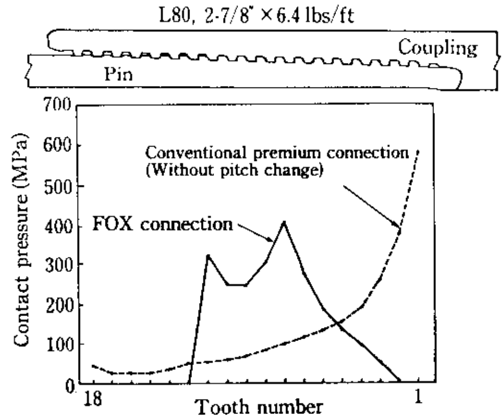

Fig. 3 Distributions of contact pressure at load flank in made-up connections

extreme thread near the seal of the coupling, and pressure decreases remarkably towards the end of the coupling. The load to make seal by make-up is balanced locally among the few threads near the seal of the coupling.

The pitch change moves the peak of the contact pressure towards the central portion of the threads, and reduces it as well. Therefore, this concept is effective in the prevention of galling during make-up or break-out.

The combination of the pitch change concept and the triple radii seal makes the FOX connection very reliable, with good anti-galling property, leak resistance, and high joint strength[4].

3 Finite Element Analysis

Very small changes of the pitch, not recognizable to the naked eye, work wonderfully, but the difference in stresses, observed on the surface, is not sufficient to be detected by the conventional strain gauging method. Since applying the pitch change concept to the premium threaded connection was totally new, the FEA was one of the most suitable verification methods.

In this section, the finite element analysis procedure is introduced, and a comparison of calculated results with experimental ones is made.

3.1 Procedure of Finite Element Analysis

The FEA procedure is classified into three processes:
(1) Pre-process (mesh generation)
(2) Solving process (calculation)
(3) Post process (output of the results)

Our objective in using FEA was to get results accurately and in time. In the pre-process, to prepare fine and accurate meshes for the model is important for obtaining good results. Dimensional accuracy can be achieved only through mathematical method. In calculating stresses and deformations of the connection, both the

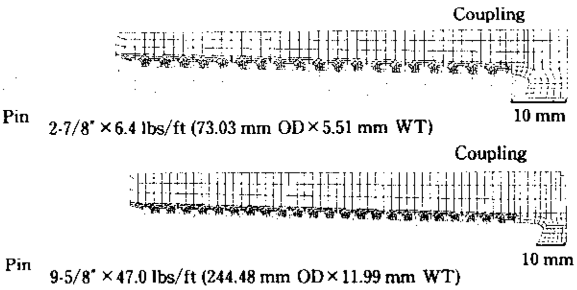

Fig. 4 Mesh diagrams of FOX connections

elastic-plastic analysis and the gap element method were applied.

The FEA procedure of the FOX connection is described in detail below.

3.1.1 Pre-process

A specific program to create the mesh data for FOX connections of any size and with any change in the thread pitch was developed. After this, the process for creating the model was easily handled, simply by entering the design factor values. The total time for this process now takes only less than an hour. Number of elements is in the thousands and its dimensional accuracy is around hundredth of a micron. Also, a pairing system of the corresponding nodal points for the gap elements is installed in the program.

Figure 4 provides examples of the mesh diagrams, created by the program, for FOX tubing with 2-7/8" OD and 6.4 lb/ft, and FOX casting with 9-5/8" OD and 47.0 lb/ft. They consist of quadrate elements with eight nodal points.

Since important areas, such as the seal zone and threads, are finely meshed, stress and strain can be calculated with adequate accuracy.

3.1.2 Solving process

A general purpose program for structural analysis, MARC, is used for the solver. Two kinds of non-linearity are involved in the analysis of the FOX connection.

(1) Non-linearity in the Stress-Strain Relation of a Material
The behavior of material is assumed to be based on incremental strain theory, Von Mises' yield condition, and the isotropic work-hardening rule.

(2) Non-linearity of Geometry
Elements, called gap element, are used to decide whether a portion of the threads or sealing area of the pin touches the corresponding portion of the coupling or not. Reaction forces are generated there during make-up or tensile loading, if the corresponding portions come into contact with each other.

3.1.3 Post-process

The displacement diagram, contour maps of stress and strain, and the like are obtained by using installed post processor.

3.2 Verification of FEA

3.2.1 Conditions

FEA results were verified by comparing them with experimental data, values of strain gauging on surfaces and the torque-turn curve. Three sizes of FOX connections, listed in **Table 1**, were used for the two types of comparison. The first comparison was of the variation of stresses and torque-turn relation during make-up, and the second was of stress distribution on surfaces in the tensile loaded condition.

Biaxial strain gauges were used for the measurements. The material used was carbon steel of API Spec. 5CT L80 grade. The stress-strain curve of the material was obtained by tensile test, and then was taken to represent elastic-plastic behavior in the FEA. The friction coefficient between pin and coupling in the calculation was assumed to be 0.06.

Table 1 FOX connections used for experiment and FEA

Dimensions	2-7/8" × 6.4 lbs/ft (73.03 mmOD, 5.51 mmWT) 3-1/2" × 9.2 lbs/ft (88.90 mmOD, 6.45 mmWT) 9-5/8" × 47.0 lbs/ft (244.48 mmOD, 11.99 mmWT)
Material	L80, carbon steel
Items	Make-up and break-out test Full scale tensile test

Note OD: Outside diameter
WT: Wall thickness

3.2.2 Results

The torque-turn curve explains the three stages of make-up, which are:

(1) Increase of contact pressure between roots and crests of the threads resulting from radial interference,
(2) Seal zone abutment,
(3) Increase of pressure on torque shoulder.

Figure 5 shows one of the torque-turn curves of the FOX connection up to stage 3 and the corresponding FEA results. In the first stage, torque increases gradually corresponding to the amount of turn due to the increase in the radial interference. The second stage is represented by the abutment indicated in the figure, where the pin seal zone comes into contact with the corresponding zone of the coupling, and the seal point slides towards the abutment. In the last stage, torque increases sharply with a small increment of turn.

The changes of stress during make-up at the two locations on the inside surface of the pin, 10 mm and

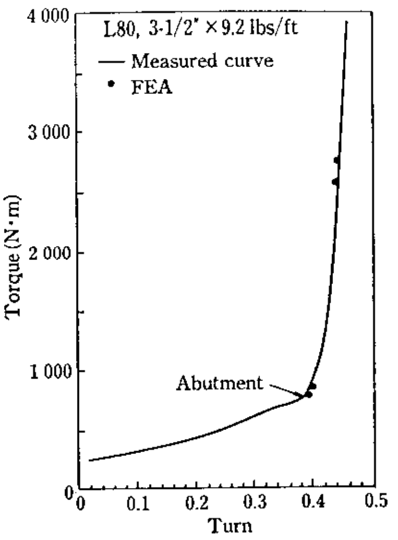

Fig. 5 Torque-turn curve of FOX connection

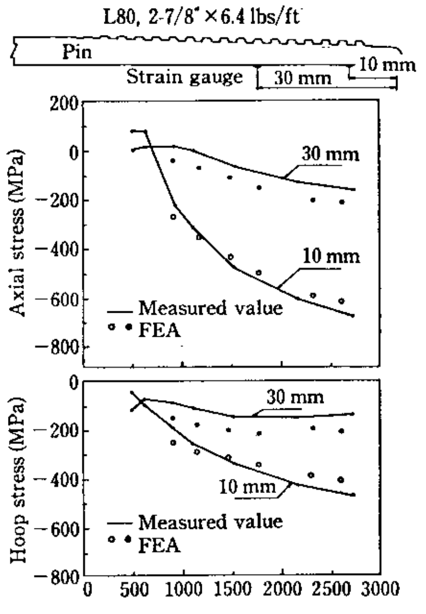

Fig. 6 Changes of pin stresses during make-up

30 mm from the pin end, are shown in **Fig. 6**. It is obvious that stress at the 10-mm position is much more influenced by the torque value than at the 30-mm position.

Figure 7 shows stress distributions on the outside surface of a coupling for three levels of tensile stress on the pipe body. Here, free tensile stress represents made-up condition. The axial load through the cross section of the coupling changes monotonously, increasing towards the center. On the other hand, the observed axial stresses on the surface show slightly different tendency from the load in the middle of the thread. Stress level is

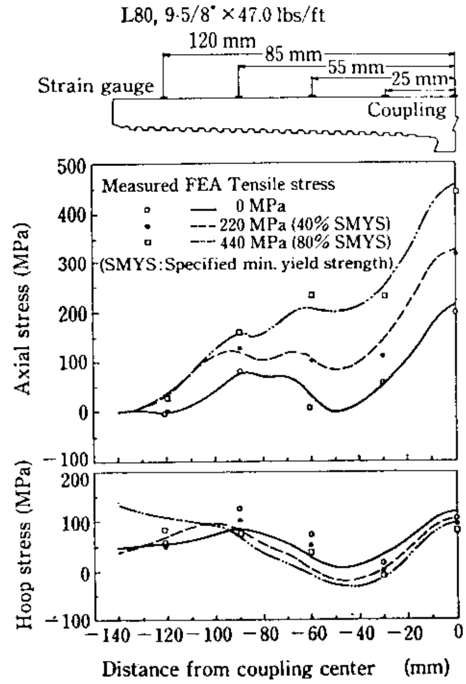

Fig. 7 Stress distributions on outside surface of made-up and tensile loaded coupling

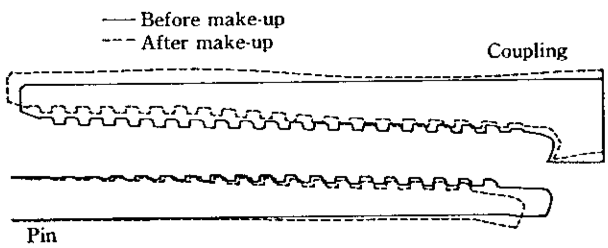

Fig. 8 Deformation of pin and coupling due to make-up (FEA)

high at the center of the coupling and almost zero at the end, but changes in a complicated manner in the middle.

This complicated variation is also seen in the deformation diagram of the coupling in **Fig. 8**, where the deformations of pin and coupling are drawn exaggeratedly.

The comparison between FEA and the strain gauging method, made on the internal surface of the pin and external surface of the coupling, has shown a good coincidence. Comparisons for other sizes of FOX connections, made but not mentioned here, also showed good matching.

4 Stress Analysis of FOX

4.1 The Effect of Pitch Change

Two pitch change points are introduced to the FOX

Table 2 Conditions of FEA on the joints of API L80 carbon steel (2-7/8″ × 6.4 lb/ft, yield strength 552 MPa)

Joint type	Amount of pitch change
1	2 × PC
2	1 × PC
3	1/2 × PC
4	0 (without pitch change)

Note PC: Standard amount of pitch change of FOX connection

connection as shown in Fig. 2, and create increasing clearances between loading flanks in two regions. The first clearance, towards the seal of the coupling, greatly improves the connection's anti-galling property during make-up and its leak resistance. The second one towards the end of the coupling works for improving the joint strength.

In this section, the amount of pitch change is studied from the following three aspects:
(1) Contact pressure on the loading flank of the thread.
(2) Axial stress distribution in the pin end region.
(3) Stress at the seal point.

4.1.1 Conditions of FEA

Four different sets of pitch change were selected for the analysis, as is listed in **Table 2**. The levels are the normal FOX pitch change, double of it, half of it, and zero which represents the conventional design.

The material is L80 grade carbon steel with 550 MPa (80 ksi) yield strength. The 2-7/8″ OD and 6.4 lb/ft tubing with the FOX design, except for pitch, is used.

4.1.2 Contact pressure on loading flank

The improvement in contact pressure distribution during make-up due to the FOX connection's design, is readily apparent in **Fig. 9**. The peak at the very end of the thread of the conventional design shifts to the first pitch change point of the thread. The pressure level at the end goes down by the increment of pitch change. Simultaneously, the newly made peak in the central zone is raised by the increment.

The amount of the first pitch change in the FOX design is shown to be one of the best choices.

The advantage of the second pitch change is to enhance joint strength reliability. The contact pressure distributions under the tensile loaded condition of 440 MPa (64 ksi), 80% of the specified minimum yield strength (SMYS) of L80, stress in the connection are shown in **Fig. 10**. The peak at the coupling end of the conventional design is pushed away to the second pitch change point.

In case of a too small second pitch change, a large scale plastic deformation, about 10%, was observed at the corner of the root around the peak area.

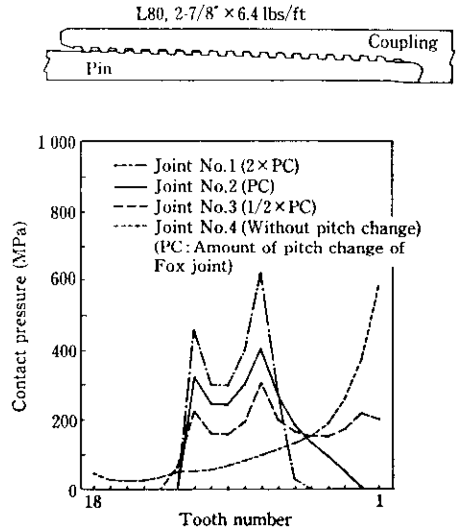

Fig. 9 Distributions of contact pressure at load flank in made-up connections

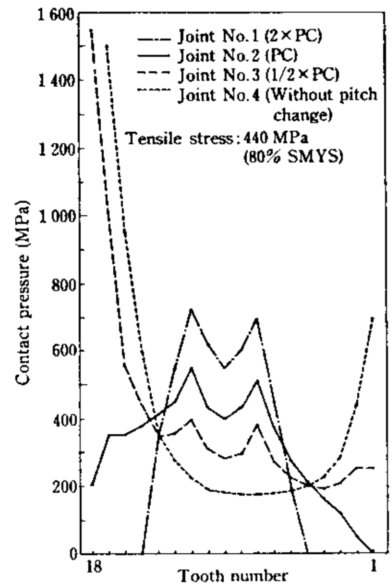

Fig. 10 Distributions of contact pressure at load flank in made-up and tensile loaded connections

4.1.3 Axial stress to support seal property

The FOX design assumes that keeping the compressive stress at the pin nose end is very important for supporting a good seal against any changes of environment such as thermal shock. The stored energy concept was introduced as an index to evaluate compressive stress distribution. The stored energy is defined as the summation of the volumetric integration of the product between stress and strain in pin and coupling. Compressive stress is used for the pin and tensile stress for the coupling.

The axial stress distributions in the four pins under

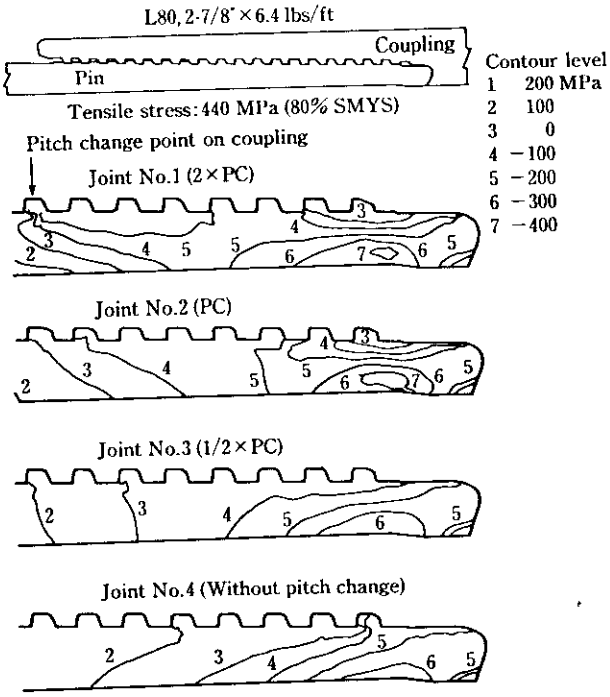

Fig. 11 Axial stress distributions in made-up and tensile loaded pins

80% of SMYS tensile loaded condition are shown in **Fig. 11**. According to the stored energy definition, the wider the area of high compressive stress is, the higher the stored energy becomes. In the case of a joint without pitch change, the compressed area is localized. Since the pitch change expands the compressive area, it also increases the stored energy.

4.1.4 Stress at seal point

Figure 12 shows an example of stress distribution in three directions around the sealing area of the made-up FOX connection. As expected, the seal point has peak compressive stress in all directions.

In order to get a gas tight seal, the surface roughness, resulting from machining, should be smoothed during make-up. For that purpose, local plastic deformation around the seal and elastic reaction force from the wall are recommended. All of these recommendations were proven to be satisfactory in the FOX connection under this analysis. All three directional stresses are in compression and their levels are extremely high when compared to the yield strength of the material itself (550 MPa). However, except for the region around the seal point, elasticity is retained, because Von Mises' stress is not high enough to cause plastic deformation. In the made-up state, the pitch change does not affect the stress distribution around the sealing area.

Figure 13 shows a sample of the seal relaxation pattern against the tensile loading. The radial stresses decrease corresponding to the increase of tensile load.

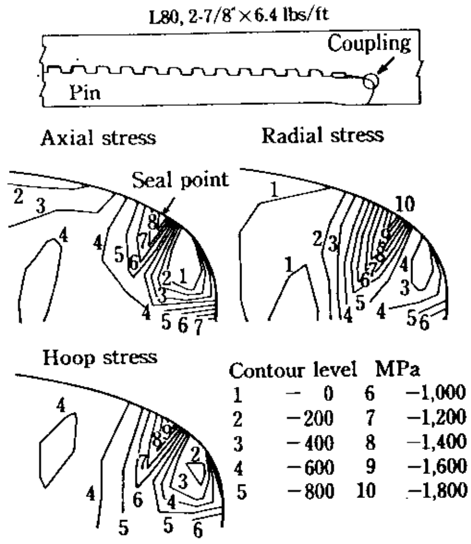

Fig. 12 Stress distributions at sealing area of made-up pin (Joint No. 2)

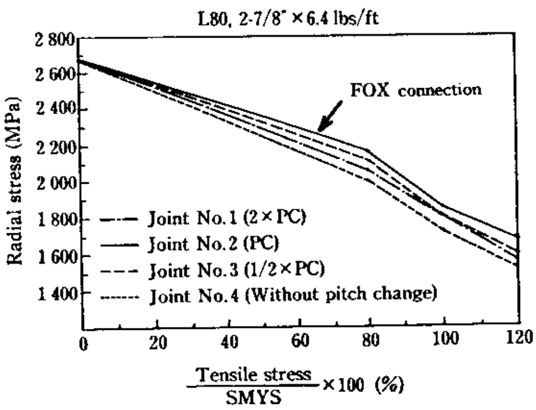

Fig. 13 Comparison of radial stresses at seal point of made-up and tensile loaded connections

But high levels of compression are retained at the seal point even when 120% of SMYS tensile load is applied to the connection. A not so big difference is observed among the four, however, the pitch changed design shows slightly improved results compared to the others.

4.2 Possibility to Estimate the Joint Strength by Using FEA

Joint efficiency is an important factor in well string design. It is simply calculated as a ratio of the cross section of the pipe body to that of the coupling where maximum tensile stress is generated. However, the actual stress state of the pin and coupling under tensile loading are not the same, being almost uni-axial in the pipe body and complicated tri-axial in the coupling. FEA is capable of providing answers to such problems as determining an outside diameter of the coupling which has a strength equal to the pipe body.

Table 3 Full scale tensile test data on the joints of API L80 carbon steel (2-7/8" × 6.4 lb/ft, special clearance coupling)

Run No.	Make-up torque (Nm)	Location of failure
1	2 440	Pipe body
2	2 440	Pipe body

Run No. 1 No. 2

Photo 1 Appearance of FOX connections after tensile test to failure (L80, 2-7/8" × 6.4 lb/ft)

4.2.1 Full scale tensile test

Table 3 shows test conditions and results. Couplings with 100% joint efficiency were used. As shown in **Photo 1**, both connections failed in the pipe body.

4.2.2 Stress analysis by FEA

FEA was used to compare the actual joint strength of pipe and coupling using the same dimensions as used above.

The plastic strain distributions in the condition loaded up to 120% tension of SMYS were shown in **Fig. 14**. The strain in pipe body is much heavier than that in the coupling. This FEA result corresponds well to the findings of the tensile test.

5 Conclusions

FEA was used to verify how the design of the FOX connection satisfies field use requirements, and the following conclusions were obtained:

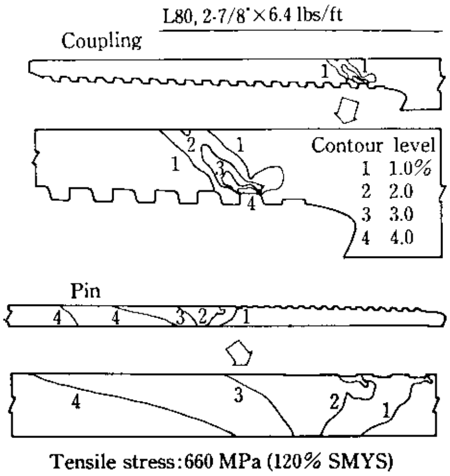

Fig. 14 Equivalent plastic strain distributions in pin and coupling of made-up and tensile loaded connections with special clearance coupling

(1) FEA was compared to strain gauging, one of the well known stress measurement methods, and a good matching was obtained. FEA is one of the most suitable means to assist in the design of connections.
(2) The analytical results revealed that the pitch change remarkably improved the contact pressure distribution along the threads. The end threads are not perfectly shaped, but chamfered at the seal end and vanishing at the coupling end side. Without a pitch change, as in conventional threaded connections, only a few extreme end threads transfer load and very little is carried through the central threads. The pitch change places a very important role on the central perfect threaded area as the major load carrier, thereby, peak load at the end is avoided, which has great advantages in improving anti-galling property, leak resistance and joint strength.
(3) By adopting the pitch change, stored energy in the connection is greately increased, thereby supporting good sealing.
(4) FEA proved that the design of the FOX connection has superior performance in all field use requirements.

References

1) Kawasaki Steel Corp. and Hunting Oilfield Services Ltd.: U.S. Patent 4 582 348
2) Kawasaki Steel Corp. and Hunting Oilfield Services Ltd.: G.B. Patent 4 732 416
3) K. Ueno, G. C. Dearden, J. K. Duxbury, and T. Maguchi: "New Concept for Load Transfer in Threaded Connections", OTC 5248, Preprint of the 18th Annual OTC, Houston (USA), May (1986), 221
4) Y. Hirano, T. Maguchi, K. Kobayashi, K. Yamamoto, K. Ueno, and J. Duxbury: "Development of Premium Threaded Connection 'FOX'", Kawasaki Steel Technical Report, No. 19 (1988), 23