On the Strength of Racks for Jack-up Units

No. 1 Report: Fatigue Behavior of Large Scale, Torch-cut and Machined High Tensile Strength Steel Racks

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This report presents the results of fatigue testing on torch cut and machined high tensile strength steel (HT80 steel) racks of 40.4 mm in module, 25 degrees in pressure angle and 63.5 mm in rim thickness. Strain distributions along compressive and tensile fillets of the racks were obtained using the strain gage method and the results were compared with those obtained using a finite element technique. The relations between the fatigue strength and the strain amplitude at the most critically stressed point in the rack fillet were then obtained utilizing the above mentioned results. Crack propagation behavior in the rack fillets was observed using plastic replicas, a magnifying glass, crack gages and the crack mark method. The results obtained are useful for fracture control of the racks.

Key words: Jack-up Unit, Torch-cut Rack, Machined Rack, Fatigue, Crack Propagation

1. Introduction

Torch-cut racks for jack-up units are used not only to elevate and lower the platform of a jack-up rig with the mesh of pinions, but also to support the platform in the ocean as constituent parts of legs. The racks, therefore, are subject to variable cyclic loads due to the structural responses caused by weather changes, as well as the vibration caused by the operation of drilling machines.

Today, fatigue design criteria do not seem to be well established for this type of rack; therefore, further research on fatigue must be conducted since these racks are subject to variable cyclic loads. In fact, there are many unknown factors that cannot be dealt with in the current design criteria due to the following:

(1) The racks are torch-cut,
(2) the rim of the racks is welded to a flexible chord and/or back-plate resulting in the fact that fillet stresses are affected considerably by these boundary conditions,
(3) these racks are designed with larger modules than those for gears and racks for general purposes, and
(4) the rack is in an ocean environment.

In this study, we have conducted fatigue testing with special emphasis on crack growth measurement in rack fillets for torch cut and machined racks of 40.4 mm in module and 1.5 modules in rim thickness. Consequently, comparison were made and discussion was carried out concerning the torch-cut and machined racks. Useful information was obtained for the fracture control of these racks.

2. Experimental Procedure

2.1 Material

The material used for the testing was a hot-rolled HT80 steel plate (high-yield-strength, quenched and tempered alloy steel plate, suitable for welding according to the ASTM standard) for full scale racks with a 127 mm thickness. The chemical analysis and method of heat treatment, as well as the room temperature mechanical properties, are shown in Tables 1 and 2, respectively.

2.2 Specimens

The rack specimens were torch-cut from a 127mm thick HT80 steel plate and then annealed at a temperature of 560°C ±20°C for 2 hours. Each specimen pair with a face width of 31.8mm, as well as each specimen with a face width of 63.5mm, was cut from the center of the cross sectional portion of the parent metal, as shown in Fig. 1. Machined specimens were then taken from 31.8mm torch-cut specimens, with care taken so that the heat-affected zone resulting from torch-cutting was not included in the final specimen.

Table 3 shows the dimensions of each rack specimen. Specimens with a face width of 63.5mm were prepared from torch-
cut specimens only. One-tooth rack specimens were adopted since it was reported by Oda(2) that the effect of neighboring teeth on the strain state in fillets was negligible. The main dimensions of rack specimens (pressure angle, fillet radius, tooth thickness, tooth width, and rim thickness) were checked with a specially designed jig, and errors in the dimensions were found to fall within a range of ±1%. The tooth form factor $Y$ in the AGMA formula(3) was then computed for the most critically stressed cross section of each rack specimen determined by Hoffer's method.(4) The coefficient of variance for the inverses of $Y$ divided by tooth width was found to be $9.78 \times 10^{-5}$; therefore, the variance in the tooth fillet stresses due to the variance in the rack specimen dimensions is concluded to be small. There was no significant difference in the variance of dimensions between torch-cut and machined specimens. The fillet surfaces of the machined specimens were polished with #180 emery paper. The fillet surface roughnesses, in the tangential direction, of both torch-cut and machined specimens are shown in Fig. 2. The $R_{max}$ value for a torch-cut specimen is found to be fifteen times as high as that for a machined specimen.

Figs. 3 and 4 show macro- and microphotographs in the vicinity of the torch-cut surface, respectively. Coarse size grains are seen in the heat affected zone, while the grain becomes finer in the depth direction leading to the parent metal zone.

Fig. 5 shows the micro-Vickers hardness measurement results taken perpendicular to the fillet surface for the torch-cut and heat affected portions. The ordinate indicates hardness and the abscissa the depth. Surface hardness is approximately Hv400 and hardness decreases as the depth is increased across the heat-affected zone. At a depth of approximately 2 mm, the hardness becomes minimal and then increases to approximately Hv300 in the parent metal zone.

Residual stresses on the torch-cut surface were measured by applying eight biaxial strain gages on the fillet surface of a rack specimen and cutting out squares, containing strain gages at the center, in the sizes from 13 mm to 15 mm and in 5 mm thicknesses, thereby releasing...
residual strains. Residual stresses $\sigma_x$ and $\sigma_y$ in the x- and y-directions (the tangential direction on the fillet surface and the tooth width direction, respectively) can be obtained by using the following formulas:

$$\sigma_x = -E/(1-\nu^2)(\varepsilon_x + \nu\varepsilon_y)$$
$$\sigma_y = -E/(1-\nu^2)(\varepsilon_y + \nu\varepsilon_x)$$

where $\varepsilon_x$ and $\varepsilon_y$ are changes in strains in the x- and y-directions, $E$ is Young's modulus (1.994 x $10^5$ Mpa), and $\nu$ is Poisson's ratio.

The averages of $\sigma_x$ and $\sigma_y$ were found to be $-65.3$ Mpa and $-180.6$ Mpa, respectively and the respective standard deviations were found to be 152.2 Mpa and 99.6 Mpa. Residual stresses $\sigma_z$ were also measured by means of X-ray method at three equidistant locations in the face width direction of a fillet resulting in compressive residual stresses of $-223$ Mpa, $-223$ Mpa, and $-220$ Mpa. It is therefore concluded that compressive stresses were mainly generated on the torch-cut surface with some variation.

2.3 Test Apparatus and Experimental Procedure

All fatigue and static loading experiments were conducted on a 0.96 MN capacity Saginomiya, closed loop, hydraulically actuated, servo-controlled mechanical test system.

2.3.1 Test Apparatus

Fig. 6 shows a schematic diagram of the loading apparatus used. Loading Rod 1 is held in place by the Saginomiya fatigue testing machine with a loading grip. The compression load is then transmitted from Loading Rod 1 to Loading Rod 2. Loading Rod 2 is guided through a hole for a length of 244 mm in order to locate the
test head on the designated line of load application. The test head is in spherical contact with the bottom end of Loading Rod 2 so that the load is applied uniformly across the face width of the racks. The test head is guided by a guide plate on the jig wall. The rack specimen is fixed to the jig with two spacer pairs and two wedge pairs. The rim surface of the rack on the spacer side is in contact with the loading jig.

2.3.2 Static Loading Test.
The static loading test was conducted in order to obtain the strain levels of the rack fillets for a given static load. For measuring strains, 5 strain gages, with active grid lengths of 1 mm, were combined to form a 10 mm row. One row of strain gages was used for each fillet surface. Strain gage locations are shown in Fig. 7. Strains were measured for the following magnitudes of load per unit face width: 3.55, 7.11, 10.6, 14.2, 17.7, and 19.5 kN/mm.

2.3.3 Fatigue Test.
Fatigue loading was essentially sinusoidal zero-compression at \( R = 0.0525 - 0.112 \) (where \( R \) equals the ratio of cyclic loads \( P_{min}/P_{max} \)). Test frequencies of the order of 2 Hz were used for load amplitudes greater than or equal to 7.63 kN/mm, and those of 3 to 5 Hz for load amplitudes less than 7.63 kN/mm. For selected specimens, strain amplitudes were measured for corresponding load amplitudes.

During fatigue testing, crack initiation was detected by applying penetrant on the surface of the rack tooth fillets and inspecting the resulting bubbles. After crack initiation, a plastic replica was made of cracks on the fillet surface after each designated load cycle interval. After a crack reached the side surface of a rack specimen, either a crack gage or a magnifying glass was used to measure the crack length on the surface at an angle of 45 degrees to the back surface of the rim of the rack specimen. The crack mark method was also applied simultaneously to a few other specimens in order to obtain the outline of the leading edges of the cracks on a fracture surface.

3. Strain Measurement and Analysis

NISA(5) and MARC(6), static finite element programs, were used to obtain the elastic strain distribution of the rack model which was set in the loading apparatus.

Fig. 8 shows the finite element grid pattern and the boundary condition used. Using the finite element method, the tangential maximum principal strains along the fillets were obtained and compared with those found using strain gages. Fig. 9 shows the relation between the tangential strain and the tangential angle for both compressive and tensile fillets. It is seen that strains obtained by means of strain gages have values slightly lower than those computed for plane stress and plane strain, while the actual condition is considered to lie between the plane stress and the plane strain. It is also seen that the ratio of maximum compressive to maximum tensile strains is slightly more than double, which far exceeds the ratio for a gear or rack with a large rim thickness (approximately 1.3).

According to the results of finite element computation, the locations of maximum tangential strain are given as \( \theta \) = 40° for the tensile fillet and \( \theta \) = 55° for the compressive fillet, while Hofer's method(3) gives \( \theta \) = 30° for both fillets. However, for gears with a small rim thickness and boundary conditions different from ours, Oda(2) obtained results similar to ours using finite element techniques. It is therefore concluded that Hofer's

Fig. 7 Strain Gage Locations

Fig. 8 Finite Element Model of Rack Specimen
Fig. 9 Relation between Tangential Strain and Tangential Angle

Fig. 10 Relation between Load and Maximum Tangential Strain in the Tensile Fillet

method is not applicable to gears or racks with a small rim thickness.

Fig. 10 shows the relation between the load and strain at the most critically stressed point in the tensile fillet. During the first cycle loading, the relation is almost linear until the strain reaches the yield point and then the relation becomes nonlinear. During the first cycle unloading, the load-strain curve is almost parallel to the linear load-strain curve before yielding. After the first cycle, the load-strain curve runs to and fro along the first cycle unloading curve. The load-strain relation for cyclic loading conforms to the above process.

4. Fatigue Test Results and Discussion

4.1 Crack Initiation and Growth Pattern

In almost all instances, cracks were first initiated on the surface of the compressive fillet and coalesced to form one large crack. It was arrested at a depth of 4 to 40 millimeters, and the length of the arrested crack tended to be greater for an increased load amplitude. Cracks were then initiated on the tensile fillet surface resulting in rack specimen failure. For a specimen subjected to a small load amplitude, cracks were initiated only on the compressive fillet surface and propagated in a plane perpendicular to the fillet surface (i.e., depth direction) without resulting in rack failure.

The above-mentioned phenomenon was previously noted by Aida et al. (7) for gears made of mild steel, but not for gears made of high tensile strength steel such as that used in this investigation. Considering that high tensile strength steel does not produce macrocracking when subjected to only cyclic compressive stresses, it can be concluded that cyclic tensile stresses were generated in the compressive fillet of the rack. Since the static loading results show that the maximum compressive strain in the compressive fillet is more than twice as high as the maximum tensile strain in the tensile fillet, the strain in the former will reach and surpass the yield point and residual compressive strain will be generated. During the course of unloading, the major portion of a rack will elastically return to the original state of strain, thus resulting in the generation of tensile stresses in a compressive fillet. Therefore, the compressive fillet will be subjected to both cyclic compressive and tensile stresses during cyclic loading. As the load amplitude increases, the tensile stress amplitude also increases and the number of load cycles to the crack initiation on the surface of a compressive fillet decreases. After initiation, a crack will propagate in the depth direction on a compressive fillet until the Mode I stress intensity factor range $\Delta K_{I}$ reaches the threshold stress intensity factor range $\Delta K_{Ith}$; therefore, the final crack length was found to become longer as the load amplitude becomes greater.

Fig. 11 shows a crack initiation pattern on the surface of a compressive fillet for a torch-cut rack of which a plastic replica was made. Cracks were initiated at several points on the surface and coalesced to form one large crack. The same initiation patterns were obtained for compressive fillets of machined racks.

Fig. 12 shows a chronological pattern of crack propagation on the surface of a tensile fillet observed from plastic replicas taken at designated intervals of
Fig. 11 Crack Propagation and Merging on the Compressive Fillet Surface

Table 4. Crack Dimensions and Cumulative Number of Load Cycles

<table>
<thead>
<tr>
<th>Number</th>
<th>Cumulative Number of Load Cycles</th>
<th>Load Condition</th>
<th>Crack Dimensions mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td></td>
<td>kN / mm</td>
<td>a</td>
</tr>
<tr>
<td>(1)</td>
<td>3.25 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(2)</td>
<td>3.55 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(3)</td>
<td>4.55 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(4)</td>
<td>5.05 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(5)</td>
<td>5.55 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(6)</td>
<td>6.05 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(7)</td>
<td>6.55 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
<tr>
<td>(8)</td>
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<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
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<td>(9)</td>
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<td>8.67 ± 7.63</td>
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</tr>
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<tr>
<td>(14)</td>
<td>10 x 10^4</td>
<td>8.67 ± 7.63</td>
<td>12.38 ± 3.90</td>
</tr>
</tbody>
</table>

Fig. 12 Crack Propagation on Tensile Fillet Surface
the load cycles. In order to generate crack marks on a fracture face, two load condition steps were applied to the specimen. Table 6 shows the load means and amplitudes for a corresponding number of load cycles. From Fig. 12, it is observed that a crack was initiated at one point in Stage (1) $N = 3.25 \times 10^4$, and then grew from Stages (2) through (4). In Stage (5), $N = 5.25 \times 10^4$, two new cracks were initiated and then grew, coalescing in Stage (8). All the cracks coalesced in Stage (10) and grew increasingly in the depth direction.

Fig. 13 shows the crack marks obtained. Numbers in brackets correspond to those in Fig. 12 and Table 4. Fig. 13 (A) shows a picture and Fig. 13 (B) shows a schematic diagram together with dimensions $a$, $b$, $C_1$, $C_2$, $C_3$, the measured values of which are listed. The $(b/a)$ value initially ranged from 0.4 to 0.6 and then leveled off around 0.8 as the crack grew. After the crack reached the side surface of the rack, all cracks coalesced to form one large crack and the leading edge of the crack, which initially appeared as two peaks, gradually coalesced to form a smooth curve.

Figs. 14 and 15 show the crack marks obtained for torch-cut racks of 31.8 mm and 63.5 mm in tooth width, respectively. The load amplitude per unit face width for the torch-cut rack of 31.8 mm in face width is the greatest and that for the machined rack is greater than that for the torch-cut rack of 63.5 mm in face width. It can be seen from Figs. 13 through 15.
that the outlines of the leading edges for torch-cut racks are rather flat compared with those for machined racks. This finding is considered to result from the fact that the torch-cut racks have more crack initiation points than the machined racks and consequently there are interventions between cracks in the initial stage of crack growth for the torch-cut racks. However, there is a slight possibility that the loading condition might influence the shape of leading edges of cracks. Fig. 16 shows a scanning electron micrograph of the fatigue fracture face of a torch-cut rack. Many defects resulting from torch-cutting are observed along the

**Load Condition 5.65 ± 5.24 KN/mm**

**Fig. 16 Scanning Electron Micrograph of Fatigue Fracture Face of Torch Cut Specimen**

**Fig. 17 Crack Propagation Pattern on the Side Surface**

**Fig. 18 Relation between Crack Length and Number of Load Cycles (Machined Specimen)**
torch-cut surface. Therefore, it was concluded that torch-cut racks tend to have more crack initiation points than machined racks.

Fig. 17 shows the direction of crack propagation on the side surface of a rack fillet. Cracks in the compressive fillet propagated on the surface at an angle of 45° to the back surface of the rim. The crack in the tensile fillet initially propagated at an angle of 45° to the back surface of the rim and then turned in a direction parallel to, but not towards, the back surface of the rim.

Fig. 18 shows the relation between crack length 'C' on the side surface and the number of load cycles 'N' for machined specimens. 'Q' indicates the number of cycles to crack initiation on the surface of the compressive fillet, and 'O' does the same for the surface of the tensile fillet. It is clearly seen that the crack growth rate on the side surface of a compressive fillet decreases as a crack grows, and eventually a crack is initiated and propagates in the tensile fillet leading to rack failure. It is also apparent that the length of the arresting crack in the compressive fillet becomes shorter as the load amplitude decreases.

4.2 S-N Curves

Fig. 19 shows the relation between the load amplitude per unit face width and the number of cycles to failure for machined and torch-cut specimens. The fatigue data on torch-cut specimens vary and the fatigue life for a given load amplitude is shorter than those for machined specimens, since the former have higher surface roughness and defects resulting from torch-cutting. It is seen from Fig. 19 that the ratio of the endurance limit for torch-cut specimens with 45 μm Max to that for machined specimens with 3 μm Max is 0.71, which falls within a range of the relation between surface factors and the surface roughness for the steels subjected to cyclic bending shown in the ASME Fatigue Strength Design Data. (8) Since measured residual stresses for the torch-cut specimens vary from tensile to compressive stresses, the residual stresses do not seem to affect the lives of torch-cut specimens positively.

Fig. 20 shows the relation between the total maximum tangential strain amplitude and the number of cycles to failure for both machined and torch-cut specimens. These data were compared with the ASME 'Best Fit' Curve (9) \( \Delta \varepsilon_t = 0.238(\sqrt{N})^{-1} + 1.29 \times 10^{-5} \) for low alloy steels which was based on the results of strain controlled push-pull testing of round bar specimens. The data on machined specimens are found to match the ASME Curve well, despite the fact that there exist average tensile strains for these data. It has been reported, however, that the average strains of this level have negligible effects on the fatigue lives N in the range of \( N = 10^2, 10^3 \). (10) In the high cycle fatigue region, \( N > 10^4 \), the average strain (stress) has significant effects on fatigue life; therefore, it is anticipated that the fatigue strength of this material is lower than that determined by the ASME Curve. It is consequently deduced that there is a difference in high cycle fatigue strength between HT80 steel and the low alloy steels on which the ASME Curve was based. 'O' indicates the data on the strain controlled push-pull testing of HT80 steel round bar specimens and these data are found to conform to the ASME Curve comparatively well. The S-N curve for the torch-cut specimens was obtained in the same form as that for the ASME Curve by using the least square method as follows:

\[ \Delta \varepsilon_t = 0.197(\sqrt{N})^{-1} + 1.02 \times 10^{-5}. \]

It is clearly seen that the fatigue strength of torch-cut specimens is lower
than that of the machined specimens. The number of cycles to crack initiation on the tensile fillet surface is also shown in Fig. 20, and it can be seen that the ratio of crack propagation life to initiation life is greater for increased strain amplitudes.

5. Conclusions

The results may be summarized as follows:

(1) Strain distribution in the investigated rack fillets was found to be in agreement with that obtained by finite element analysis, and in the elastic range, the maximum compressive strain level was found to be slightly more than twice as high as the maximum tensile strain level.

(2) During fatigue testing, cracks were found to be first initiated on the surface of a compressive fillet, but ultimately stopped growing. Cracks were then initiated on the surface of a tensile fillet resulting in rack failure.

(3) Defects resulting from torch-cutting were observed on the surfaces of torch-cut specimens and the surface roughness for the torch-cut specimens was found to be remarkably higher than that for the machined specimens. Torch-cut specimens, therefore, had more crack initiation points than machined specimens and these cracks intervened in the early stages of crack propagation resulting in the outlines of the leading edges of the surface cracks for the torch-cut specimens which tended to be flatter than those for the machined specimens.

(4) The fatigue strength of each rack was plotted in terms of local maximum tangential strain amplitude, and the fatigue strengths of machined racks were found to match those determined by the ASME 'Best Fit' Curve for low alloy steels. The fatigue strength of torch-cut racks, evaluated as \( \Delta e_{\text{f}} = 0.197 \cdot (\sqrt{N})^{-1} + 0.02 \cdot 10^{-3} \) on average, proved to have a lower value than that determined by the ASME Curve, and the former varied considerably.

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