Fatigue of reinforcing bars during hydro-demolition

C W K Hyland$^{1,3}$, A Ouwejan$^2$

$^1$Hyland Consultants Ltd, Level 10, 300 Queen St, Auckland 1010, New Zealand
$^2$Metlab Ltd, 1 Bushlands Place, Papakura, Auckland 2113, New Zealand
$^3$ Email: clark@hylandconsultants.com

Abstract. Reinforcing steel fractured during hydro-demolition of a reinforced concrete pier head due to low cycle flexural fatigue from vibration caused by impact of the high pressure water jet on the exposed length of the bars. Research into the fatigue performance of steel reinforcing steel tends to focus on the high cycle axial performance in reinforced concrete members and re-bending behaviour. However with the increasing use of hydro-demolition of concrete structures as part of remediation works care is required to ensure the steel reinforcement exposed to the high pressure jet of water is not going to suffer relatively low cycle flexural damage that may compromise the designed performance of the completed reinforced concrete structure. This paper describes the failure assessment, fatigue analysis, and metallographic examination that was undertaken. It was found that the rib to flank transition radius on the reinforcement steel was small enough to cause a significant stress concentration effect and was the location of fatigue crack growth. A relatively simple analysis using the maximum unrestrained cantilevered bar length and force exerted by the water jet was used to calculate the maximum expected bending moment. This was compared to the bending capacity at initiation of yielding at the rib flank transition accounting for stress concentration effects. This showed that the observed cyclic reversing ductile crack growth and fracture of the H25 bars was consistent with the loading applied. A method is proposed based on these observations to assess suitable limits for unrestrained bar lengths or maximum working offset of the water jet from the point of bar restraint when undertaking hydro-demolition work. The fatigue critical performance requirements of AS/NZS4671 500E bars are also therefore compared with those of BS4449:2005 and PN EN/ISO 15630-1:2011 for comparable 500C bars

1. Introduction

This paper describes an investigation into the causes of the bending, cracking and fracture of a number of reinforcing steel bars in a pier head that occurred during hydro-demolition of concrete around them.

Three H25 vertical bars with long unrestrained lengths on the same face of the pier head fractured and others developed fine flexural fatigue cracking at the rib flank transitions near their base during the hydro-demolition of the concrete.

Research into the fatigue performance of steel reinforcing steel bars tends to focus on their high cycle axial performance in reinforced concrete members and bending behaviour rather than low cycle flexural fatigue crack growth and fracture [1][2].

The site observations, metallographic examination undertaken and the engineering calculations prepared to assist with the assessment of the failure analysis are described.

A method is then presented for assessing appropriate maximum unrestrained bar lengths or working offsets for the jet relative to the point of bar restraint when undertaking hydro-demolition. The method accounts for the stress concentration effect at the rib flank transition.

The manufacturing requirements of AS/NZS4671 [3] with respect to controlling the rib flank transition relevant to fatigue performance are also compared to those of BS4449:2005 [4] and PN EN/ISO 15630-1:2011 [5] for similar 500C bars.
2. Methodology

2.1 Site inspection
An inspection was made of the pier heads after the fractures occurred. The fractured H25 stubs of East Pier Head bars designated with identification numbers EN5 and EN7 were removed using a disc cutter for metallographic examination. The longer portion of bar EN7 on the other side of the fracture was also recovered.

2.2. Determination of hydro-demolition method and sequence
A drawing was prepared by site staff identifying the location of each bar, which had fractured, or had been examined using MPI. Hydro-demolition sequence diagrams with dates and extent demolished were prepared from site records and matched with photographs taken during the works to identify what amount of bar restraint was in place during eth process and particularly at the time of the fractures.

2.3. Materials test reports and testing
Steel mill certificates were sourced for the bars supplied, along with bend, tensile and chemical analysis tests that had been conducted on specimens extracted from one of the fractured H25 bars.

2.4. Magnetic particle inspections
Magnetic particle inspections had been previously been undertaken by others using dual permanent magnets and Ardox 8901 white contrast with Ardox 800/3 black ink in accordance with AS1171:1998 [6] (“MPI”). This had found cracks in a number of bars that hadn’t fractured.

2.5. Metallographic procedure
The fracture samples from EN5 and EN7 were prepared for metallographic examination at macro and micro level. The fracture faces were examined under a Meiji brand stereo microscope before the two faces were scrubbed with a hand-brush under running water. The faces were then sprayed in alcohol, dried and re-examined under the stereo microscope.

The longer portion of bar EN7 was cut 100 mm from the fracture to allow a smaller sample to handle. This length was wire-brushed around the diameter to remove dirt and scale and examined under the stereo microscope. Three sections were mounted from the area at and near the fracture face, and two sections were mounted at an area 1300-1400 mm away from the fracture. The sections were cold-cut on a metallographic cut-off saw flooded with coolant, and cold-mounted in resin so as not to induce any heat onto the samples.

The mounts were then ground and polished to a 1 micron diamond finish and examined on a metallurgical microscope in the as-polished condition. Etching to reveal the microstructure was carried out using 2% Nitric acid in alcohol.

Micro-hardness testing was carried out on a calibrated Matsuzawa brand micro-hardness tester at various locations at and around the ribs and also away from the ribs.

3. Results

3.1. Site inspection findings
Some of the H25 bars were found to have been bent up to 16 degrees either side of vertical but hadn’t fractured. A number of the H25 bars had also been manually straightened since the fracturing of the bars in question (Figure 3). The larger diameter H40 bars however had not sustained any permanent deformation and appeared to have remained in the condition in which they had been originally cast into the concrete.
3.2. **Hydro-demolition method and sequence**

The hydro demolition had been conducted using a machine that had one jet operating at 1450 bar through a 2.3 mm diameter nozzle. Its movement and angle of attack to concrete surfaces could be adjusted by the operator. Restraining tie bars to the vertical bars had been removed progressively by oxy acetylene cutting as they were exposed by the hydro-demolition process. Each pier head had taken approximately 10 days to remove the concrete down to the original construction joint level.

3.3. **Findings from Steel Mill Certificates and Testing**

The steel mill certificates and specific bend, tensile and chemical analysis tests of specimens extracted from one of the fractured H25 bars showed that they conformed with the manufacturing requirements for D500E 25mm micro-alloy bars to AS/NZS 4671.

3.4. **Findings from magnetic particle inspections**

The MPI reports showed that significant cracking occurred at the base of all the H25 bars on the north face of the east pier head at and up to 75 mm above the main fracture locations. This cracking was consistent with fully reversed cyclic displacement of the vertical bar acting as a cantilever being buffeted by the water jet.

3.5 **Observations on the stereo microscope**

The outer portions of the failure surfaces of the fracture in EN7 (Figure 4 and Figure 13) had a distinctive stepped profile (Figure 10 and Figure 15) consisting of relatively flat transverse fatigue cracks joined to the adjacent fatigue crack above and below by sloping failure surfaces (Figure 5). The stepped profiles on the failure surfaces were consistent with fatigue cracking initiating at the rib flank transition radii and stepping by means of localised shear failure at 45 degrees to the cracks above and below as crack growth progressed into the bar (Figure 10 to 13).

The cracking and fracture followed the spiral of the ribs, and cracking occurred predominantly at the rib-flank transition (Figure 4 and Figure 5). The reinforcing bar ribs had a varying rib flank inclination pattern with differing rib flank inclination angles on each face of the rib (Figure 7). The rib flank inclination was measured perpendicular to a rib to be 58 degrees with a transition radius of 0.8 mm. The rib flank inclination angle on another was 42 degrees with a transition radius of 1.1 mm. This angle was slightly less than the rib flank inclination required of 45 degrees by cl 7.4.2.2 AS/NZS 4671.

3.6 **Observations on the metallurgical microscope**

On one side of the bar at the ribs there are a series of cracks and compression of the ferrite/pearlite microstructure. This is accompanied by some areas which appear to have ‘bulged’ and smaller micro-cracks have occurred in these regions, (Figure 7 to Figure 9). This is consistent with low cycle high stress range loading having occurred during crack development.

Micro-hardness testing in this compressed region shows a hardness of 310-325HV0.5. By comparison, at the outside diameter away from cracking or compressed microstructure the hardness was measured to be 250HV0.5. 8mm below the surface in an unaffected area the hardness was measured to be 235-245HV0.5.

At the opposite side of the diameter there is no such compression of the microstructure and no cracks evident. Micro-hardness testing in this region shows a hardness of 225-235HV0.5. At the fracture face of EN7 shown in Figure 13 there is cracking perpendicular to the main crack surface at the edge of the final crack process zone indicating volumetric plastic deformation (Figure 14).
Figure 1 West Pier Head

Figure 2 East Pier Head with H25 bars on north face bent inwards

Figure 3 Bar stub in East Pier Head

Figure 4 EN7 fracture surface and fatigue cracking at adjacent rib flank transition

Figure 5 Crack at rib flank of EN7 with 0.8mm transition radius (90 degrees to rib)

Figure 6 Varying rib profile on EN7 (90 degrees to rib)
**Figure 7** Etched cracks in EN7 rib flank transition radius above fracture surface (50x)

**Figure 8** Etched localised bulging and compression deformation of grain structure near crack (200x)

**Figure 9** Bulging of surface at crack fronts indicating compressive yielding (100x)

**Figure 10** Stepping crack with flat fatigue cracks connected by sloping shear surfaces (50x)

**Figure 11** Etched crack steps in Figure 11 (200x)

**Figure 12** Etched rib flank transition 1300mm away from fracture in EN7 (100x)
Further along the fracture face there is stepping and smaller cracking similar to that observed in Figure 10. Examination of the profile of the ribs away from the fracture surface shows a crack in the tighter portion of the varying rib to flank transition angle in one of the ribs (Figure 5 compared with Figure 6). Fatigue cracking occurred at the base of a number of rib flank transitions up to two or three ribs or up to 75 mm away from the fracture surface. This is also consistent with the MPI site findings.

Cross-sections were also taken 1300-1400mm away from the fracture surfaces to provide a control. These sections showed the same rib profile as nearer the fracture. Examination of the microstructure around the ribs in these locations showed no deformation of the hot rolled ferrite/pearlite microstructure well distant from the fractures (Figure 12).

It is reasonable to conclude therefore that the compression bulging and cracking of the microstructure at the rib transition near the fracture was a result of localised cold working and not due to manufacture. Considering this compression bulging was near the fracture it is likely that this occurred during the failure process.

There is banding of the ferrite/pearlite phases in the microstructure and non-metallic inclusions running parallel with the rolling direction. However there is no microstructural evidence that these contributed to the failure. These would not be expected to have contributed significantly to fatigue crack initiation or growth as they would have been transverse to the crack propagation plane.

3.7 Discussion of Observations

The failure surface of bar EN7 shows that the development of the majority of the fatigue cracking occurred in a short number of high stress range cycles consistent with low cycle fatigue. The final crack tip process zone is approximately 2.5 mm deep (Figure 8). It appears that 4 or 5 high stress reversing cycles occurred before fracture. This is based on the crack process zone surface beach marking indicated by the slightly varied angles of the stepped failure surfaces of sample EN7.

The large crack tip process zone failure surface marks on the EN7 fracture surface are consistent with steel with high ductility and therefore large localised plastic zones ahead of the crack tip and ductile crack growth.

The final fracture appears to have occurred once the fatigue crack grew to approximately 8 mm depth from the bar surface (Figure 14). This is because the process zone on the right side is relatively bright and hasn’t been dulled by a reversing compressive action, unlike the other stepped crack process zones either side of the bar centreline.

A photo transverse to the failure surface of EN7 also shows the final process zone slightly raised above the previous crack surface indicating it hadn’t been compressed by a reversing compressive stress (Figure 15).

The longitudinal crack perpendicular to the fracture surface at the start of the final process zone appears to be due to both localised constant volume plastic volumetric strain and necking effects as the crack tip process zone elongated as the crack opened. Similar cracks at the prior crack tip process zones are apparent. Such cracking is consistent with very high bending stress cycles in the bar.

At the end of the final process zone the bar fracture then appears to have progressed into less constrained gross section fibrous fracture indicted by significant micro-void coalescence in the centre region of the bar. It seems that the fracture then finished with a small zone of cleavage fracture at the bottom left corner. This is characterised by the swirling leaf-like pattern possibly originating from localised non-metallic inclusions.

Bar EN5 had similar characteristics however the fracture plane shows greater distinct steps on each side of the fracture with a large vertical step the height of a rib and runs across the surface at 45 degrees to the longitudinal plane of the bar. The longitudinal plane runs along the bar between the two longitudinal ribs on each side (Figure 16).

4 Results of the failure analysis

The force applied by the hydro demolition jet was estimated based on the 1450 bar working pressure through its 2.3 mm nozzle, to be 602 N. This is likely to have been applied to the top of the vertical
bars cantilevering 1.85 metres above the construction joint, as the hydro-demolition unit was seated on top of the pier head or adjacent to it with its jet angled downwards when exposing these bars.

Figure 13 The Fracture surface of EN7 showing low cycle fatigue crack development with large stepped crack growth marks at slightly varying angles each side of the dull fibrous fracture central area. The brighter band to the right of the central fibrous fracture zone is likely the final fatigue crack growth step prior to fracture progressing to gross section fibrous fracture. A portion of cleavage fracture with a swirling pattern is also apparent in the lower left of the failure surface.
Figure 14 Cross section taken at the crack to the right of the final low cycle fatigue crack process zone in Figure 14. This shows the slightly uplifted nature of the final process zone to the left of the crack and the deformed grain structure indicating volumetric plastic deformation as the crack tip elongated on opening and the crack front progressed.

Figure 15 Fracture surface of EN5 showing vertically displaced steps
Even accounting for a 30 degree angle of attack of the jet giving a lateral component of thrust of 425 N, this would result in a bending moment of at least 0.79 kNm. This compares to a yield moment in the H25 of 0.83 kNm, calculated using the tensile test result of fy = 542 MPa. So the bars could have been loaded to close to gross section yield by the water jet. However this would not have been sufficient on its own to cause the fractures without the additional effect of stress concentration at the rib flank transition.

Based on the metallographic observations a static normal stress concentration factor of

\[ K_t = A \left( \frac{r}{d} \right)^b = 2.16 \]  

(1)

was calculated using the measured rib flank transition radius of \( r = 0.8 \) mm, bar diameter \( d = 25 \) mm, diameter at rib \( D = 29 \) mm, \( A = 0.97722 \) and \( b = -0.23093 \) [7]. The notch sensitivity was calculated to be \( q = 0.69 \) from the Kuhn-Hardrath formula [8].

This all resulted in a dynamic or fatigue stress concentration factor of

\[ K_f = 1 + q(K_t - 1) = 1.8 \]  

(2)

for steel with ultimate tensile strength \( UTS = 550 \) MPa.

The cantilevered H25 bars were therefore susceptible to localised plastic strain reversals at the rib flank transitions due to the stress concentration effect at bending moments as low as 0.46 kNm, which is well below the bending moment able to have been applied by the water jet. The H40 bars with similar unrestrained cantilever length of 1.85 m are likely to have been subjected to similar bending moments of 0.79 kNm during the hydro-demolition. However the average yield moment of the H40 based on the tensile properties listed on the mill certificates provided is 3.41 kNm. This is much greater than the demand on them even accounting for stress concentration effects at the rib flank transition. So no permanent damage due to low-cycle fatigue was expected to have occurred in the H40 bars from the hydro-demolition. However a further 10% of these were tested on site for cracks using the Magnetic Particle Inspection method, which confirmed that no cracking had occurred.

5 Method of assessment of unrestrained bar length during hydro-demolition

It is proposed that the maximum unrestrained length of any reinforcing steel bar can be calculated using equations (1) and (2) and any combination of end restraint conditions such as cantilevered, fixed or pin ended.

\[ P^*_{jet} \]

\[ L_{\text{max}} \]

**Figure 16** Unrestrained cantilever length of bar \( L_{\text{max}} \) relative to point of restraint and location of application of hydro-demolition jet

The limiting bending moment so that yield is prevented from occurring at the rib flank transition is

\[ M^* \leq \phi M_{cr} = \phi \frac{\pi}{32} \frac{d^3}{2} f_y \]  

(3)

for \( \phi = 0.9 \).
For the H25 and H40 bars in this case with characteristic $f_y = 500$MPa, assuming the same rib profiles and rib flank transition radius of 0.8 mm with notch sensitivity $q = 0.7$, and horizontal water jet force of 602 N, the appropriate unrestrained cantilever lengths or offset of the jet from the point of bar fixity $L_{max}$ (Figure 16) would have been as shown in Table 1.

| Bar   | D/d | A      | b        | Kt  | Kf   | $\phi M_{cr}$ (kNm) | $L_{max}$ (mm) |
|-------|-----|--------|----------|-----|------|---------------------|----------------|
| H25   | 1.16| 0.97722| -0.23093| 2.16| 1.80 | 0.383               | 635            |
| H40   | 1.10| 1.01650| -0.21548| 2.36| 1.95 | 1.449               | 2410           |

Table 1 Example maximum unrestrained cantilever lengths or working offset of the jet from the point of bar fixity using Equation (3)

6 Comparison of fatigue critical provisions of AS/NZS 4671 with BS and EN Standards

The steel mill certificates, the specific tensile and bend testing, and the chemical analyses showed that the bars complied with the tensile, bend and chemical analysis requirements of AS/NZS 4671:2001.

The rib height and rib flank inclination angles measured in a few locations were generally consistent with the requirements of AS/NZS 4671. The rib flank transition radii of 0.8 mm are a little larger but comparable to those of M24 PC8.8 bolts which the authors have observed to be in the order of 0.3 mm. The fatigue category of bolts in the Steel Structures Standard NZS 3404:1997[9] is 36 compared to that of typical hot rolled steel sections of 160. The Concrete Structures Standard NZS3101 [10] appears to assume that reinforcing bars would have a fatigue performance comparable to a Steel Structures Standard NZS 3404 [7] hot rolled section by designating them to have fatigue category of 150.

The fatigue strength of steel reinforcing bars is generally recognised to be limited by the stress concentration effect of the rib flank transition radius. However there are no prescribed fatigue performance requirements for bar manufacturer’s to comply with in AS/NZS 4671. It appears that AS/NZS4671 relies solely on the level of uniform elongation of the steel in a tensile test to provide reliable fatigue performance [11].

The British and European Standards BS4449:2005 and PN-EN ISO 15630-1:2011 specify minimum fatigue performance for bar manufacturer to ensure compliance with, for B500C bars which are comparable in many ways to AS/NZS 4671 500E bars.

BS4449:2005 and PN EN/ISO 15630-1:2011 require reversed bending for 25 and 40 mm diameter B500C bars. Whereas AS/NZS 4671 does not require reversed bend testing of 500E H25 or H40 bars which may have exposed the performance limiting stress concentration effect of the tight rib flank transition radius.

In summary the bars supplied appear to satisfy the requirements of AS/NZS 4671 but the Standard does not adequately specify critical fatigue performance requirements or rib flank radii limits for the bars to achieve the fatigue performance expected from comparable bars manufactured compliant with BS4449:2005 [12] and PN EN/ISO 15630-1:2011.

7 Conclusions

The force exerted by the hydro demolition jet were sufficient to develop gross section flexural yield stress in the H25 bars on the north face of the east pier head once the restraint of the concrete and tie bars were removed leaving the bars to cantilever 1.85 m above the lower concrete surface. However this would not have been sufficient on its own to cause the fractures without the additional effect of stress concentration at the rib flank transition.

A relatively simple analysis using the maximum unrestrained cantilevered bar length and force exerted by the water jet was used to calculate the maximum expected bending moment. This was compared to the bending capacity at initiation of yielding at the rib flank transition accounting for
stress concentration effects. This showed that the cyclic reversing ductile crack growth and fracture of the H25 bars was consistent with the loading applied.

A method based on this finding is proposed to assess suitable limits for unrestrained bar lengths when planning hydro-demolition work.

The small rib flank transition radii measured on the H25 bars EN5 and EN7 extracted from the north face of the east pier head likely contributed to rapid reversing ductile crack growth or very low cycle fatigue as the vertically cantilevering H25 bars vibrated in response to the attack of the hydro demolition jet. The force exerted by the hydro demolition jet was however not sufficient to develop the same level of flexural stress in the H40 bars of the same length.

There was sufficient evidence to conclude that the H25 bars conformed to the requirements of AS/NZS 4671 in terms of tensile, bend and chemical analysis properties. Similarly the measurements of the ribs indicate the rib height inclination angles were generally consistent with requirements of AS/NZS 4671. However AS/NZS 4671 does not prescribe a minimum rib flank transition radius. Nor does it prescribe the fatigue performance criteria for steel manufacturers, or rebend test requirements for H25 and H40 bars. Whereas these are required by BS4449:2005 and PN EN/ISO 15630-1:2011 for comparable 500C bars in Europe.

The performance and detailed testing and examination of these bars raises concerns that bars compliant with AS/NZS 4671 may not give high and low cycle fatigue performance comparable to the equivalent British and European standards as perhaps expected by the New Zealand Concrete Structures Standard NZS3101.

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