The Effect of Geometry on the Fatigue Life of Overhead Line Hardware

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Abstract

Bow shackle failures, over the years, raised the question whether these failures are attributed to microstructural changes along the profile of the shackle or due to the geometry of the shackle. Bow shackles forged from 080M40 (EN8) material were subjected to different heat treatments in order to alter the microstructure thereof. The shackles were 3D-scanned prior to fatigue testing, and the data points were imported into engineering simulation software (ANSYS), to build a finite element model of each shackle tested. The shackles were subjected to five different fatigue load cases, which represented typical loads experienced at termination points for an overhead line with a span length of 400 m, with changes in conductor type, configuration, wind and ice loading. The fatigue tests revealed that the improvement in fatigue performance with an increase in hardness was limited to the lower load levels. In addition, the finite element model indicated that the misalignment of the bolt holes results in unequal load distribution between the two legs, with a considerable increase in the bending stress experienced by the leg carrying the higher loading. The influence of the bow shape of the shackle was confirmed by testing straight-leg shackles also manufactured from 080M40 material, which outperformed the fatigue performance of the bow shackles. Furthermore, misalignment of the bolt holes for the straight shackles did not have the same detrimental effect compared to the bow shackle. Although the change in microstructure does influence the fatigue performance, this investigation concludes that the combined influences of the curved leg and misalignment of the bolt holes pose a greater impact on the fatigue performance of bow shackles than microstructure. Furthermore, the fatigue performance of line hardware shackles is significantly improved by changing the geometry of the shackle from a curved leg to a straight leg.

Keywords: bow shackle; fatigue; geometry; misalignment; straight shackle

1. INTRODUCTION

The prime function of overhead line hardware is to connect the phase conductor to the insulators and the insulators to the structure (tower) [1]. The rounded design of the bow shackle allows it to handle loads at different angles, hence making it ideal to be used within a hardware assembly, as it can assist to counter any possible misalignment within the assembly due to slight line deviations associated with tower position.

The shackle size and strength class will differ within the hardware assembly and is depending on the mechanical loading introduced at a specific attachment point. Therefore, the shackle with the highest strength rating will be positioned at the tower attachment point.

As illustrated by the red dotted circles in Fig. 1, shackles are used throughout a bundle assembly in a single attachment manner, of which the tower attachment shackles present the highest risk and impact when failing, as it will result in the conductor bundle to fall to ground and cause a line outage. The failure of shackles attaching the conductor to the hardware assembly is less critical as it will not immediately result in the conductor falling to ground. However, in the case of a single conductor configuration, both the tower and conductor attachment shackles are critical as failure of either of the two will result in the conductor to fall to ground.

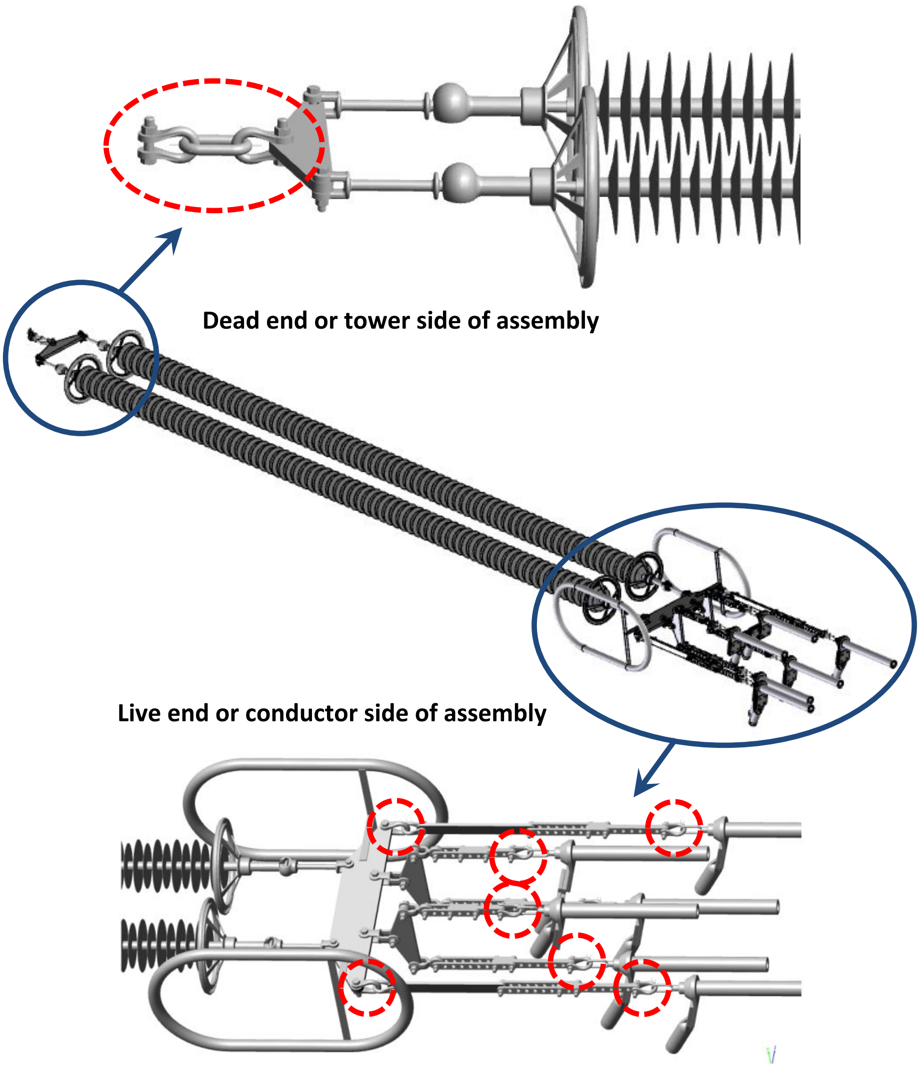

Fig. 1. Strain assembly for a 765 kV six bundle conductor configuration (Drawing not to scale)

Quench and temper heat treatment methods are typically used to increase the mechanical strength of line hardware, which often results into a nonhomogeneous microstructure along the profile of especially forged components with a complex geometry, due to the difference in cooling rate for the different cross sectional areas [3].

Therefore, when bow shackle failures occurred, as a result of fatigue damage on certain span lengths (sections) on the 765 kV electrical network in particular, raised the question if poor control during the heat treatment of bow shackles as identified by failure investigations conducted [2], was the only contributed factor towards these failures.

This study investigates the influence of microstructure and geometry on the fatigue behaviour of forged line hardware in specific bow shackles.

2. EXPERIMENTAL METHODS

2.1. Manufacturing of test samples

Bow and straight shackles were hammer forged from 35 mm diameter 080M40 (EN8) material, using a closed die system making use of a Banning pneumatic hammer forged press. The 300 mm long billets were induction heated between 1100 °C and 1250 °C and the forging temperature was between 950 °C and 1250 °C. The holes within the eye section were punched immediately after the component was forged.

After heat treatment the shackles were galvanized making use of a centrifuge galvanizing method. The bath had a zinc content of 99.7 % and the temperature of the melted zinc was maintained at 450 °C. The shackles were removed before solidification of the zinc could occur on the component surface and placed in a centrifuge, then spun for several seconds to remove excess zinc from the surface. Thereafter, the components were transferred to a quench tank where it is cooled to allow handling.

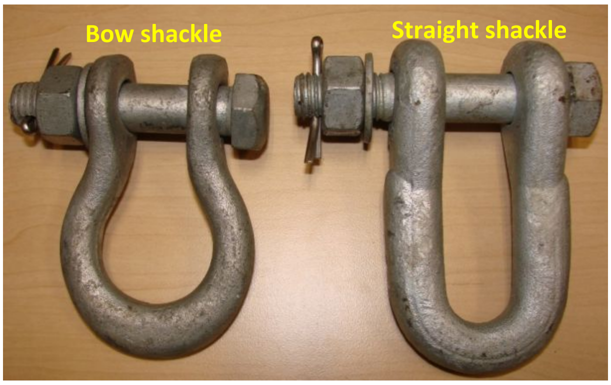

Fig. 2. Geometry differences between a bow and straight shackle

2.2. Heat treatment of test samples

The straight shackles were only subjected to a normalizing heat treatment and the desired hardness for the final product was specified to be between 152 and 207 Brinell hardness number (BHN) [5]. The normalizing heat treatment was conducted in a protective (controlled) atmosphere using propane gas to prevent scaling of the component surface. The components were placed in baskets and loaded into the preheated furnace at 820 °C, subsequently the temperature was increased to 920 °C within 75 minutes. The temperature was maintained for 2½ hours, after which the components were removed and air cooled to room temperature while still in the baskets.

The bow shackles underwent the same normalizing heat treatment as the straight shackles. In order to alter the microstructure the shackles were subjected to two different harden and temper heat treatments namely “AR” (As received) and “HTM” (Heat treatment modification).

AR-shackle samples were subjected to a heat treatment process similar as the shackles that failed in-service. The differences in the two heat treatment processes are summarized below.

i) ***Austenitization heat treatment***: Following the normalizing heat treatment, the components were:

AR: reheated to 880 °C for approximately 40 minutes, followed by quenching in oil which was maintained at a temperature range between 60 °C and 80 °C.

HTM: reheated to 880 °C for approximately 1 hour and components were quenched in running water.

ii) Tempering heat treatment: The last stage of the heat treatment process was tempering, which was conducted at:

AR: 515 °C for 4 hours followed by oil quenching.

HTM: 520 °C for 4 hours and quenched in running water.

2.3. Testing

The high cycle fatigue testing was conducted on a MTS Landmark servo-hydraulic test machine. As testing was not conducted on standard fatigue specimens, but on a component, shackles, the test requirements of ASTM E466 – 96 [6], were used as a guideline to develop a force controlled constant amplitude axial fatigue test procedure in MTS TestSuite Multipurpose Elite (mpe) software, used for setting the test parameters and record the test data.

As depicted in Fig. 3 a back-to-back shackle arrangement was used to simulate installation practices. The tongue fittings measuring 20 mm in thickness and a bolt hole of 20 mm were used to connect the back-to-back shackle arrangement to the MTS test machine grips.

The bolts used were not the standard 8.8 grade bolts that are supplied with the 210 kN shackles, but was machined from martensitic stainless steel, which provided improved mechanical properties compared to that of the 8.8 grade material, in order to minimize the deformation associated when subjecting the bolt to bending loads when the shackle is loaded in tension.

Fig. 3. Shackle fatigue testing setup

The selection of which hardware strength class to be used for a hardware assembly is determined by the ultimate tensile strength of the conductor attached to it; thus hardware rated at 210 kN can accommodate different conductor types and configurations. Therefore the mechanical loading introduced to the hardware assembly is directly linked to the tension within the conductor, which is affected by several factors such as conductor type, temperature, span length, wind and ice loading.

In house developed software titled Tower Loader SANS v2.3d based on SANS 10280 [7] was utilized to calculate the different loading conditions for a 210 kN rated hardware assembly. The loading conditions were subdivided into fatigue load cases and are summarised in Table 1. The amplitude (lower and upper limits) is expressed in load (kN) based on the percentage of the ultimate tensile strength of the shackles, which was taken as 210 kN.

Table 1: Fatigue load cases

Fatigue load case	Lower limit		Upper limit	
	(kN)	(% of UTS)	(kN)	(% of UTS)
1	37.8	18	52.5	25
2	52.5	25	71.4	34
3	71.4	34	100.8	48
4	100.8	48	121.8	58
5	121.8	58	147.0	70

Prior to conducting the high cycle fatigue testing shackles were 3D scanned making use of a MetraSCAN 210 manual scanner paired with a C-Track optical tracker to enable dynamic referencing and automatic alignment during scanning. In order to import the 3D scan data directly into the ANSYS finite element analyse (FEA) package, the VX-elements software, Version 4.1 were used to capture and process data points.

To prevent the lasers from reflecting, which can cause distorted and missing data a flat white spray paint was applied to the surface of the shackles prior to scanning. In order to gain access with the scanner to all possible scanning angles to improve the accuracy of the scan, the shackles were suspended from the scanner stand. Alignment prep marks were place on the scanner stand support beam and shackles in order to assist with the alignment of the shackles to ensure that each shackle is position in the same location prior to scanning.

3. RESULTS

As depicted in Fig. 4, significant improving in fatigue performance was obtained with the HTM-shackles, which had a higher hardness than the AR-shackles, due to their altered microstructure. However, the improved fatigue performance was limited to the lower loading cases, as no improvement in fatigue life was obtained from load case 3 onwards.

In addition Fig. 4 depicted the difference in typical fracture appearance between the AR and HTM-shackles. The AR-fracture surface reveals a mix mode fracture with the formation of a shear lip at the final fracture, indicating the ductile nature of the AR-shackles (material). The HTM-shackles reveal a brittle like fracture surface with only a small fatigue propagation area compared the AR-fracture surface where fatigue crack propagation occurred over approximately 25% of the fracture surface.

The straight leg shackles were not tested to destruction, after 25 million cycles the test was stopped and the shackles were subjected to a fluorescent magnetic particle inspection to verity if any cracking had occurred. No cracking was detected and it was confirmed by dissecting the shackles and conducting a metallurgical examination on the shackle material, no surface cracking was observed.

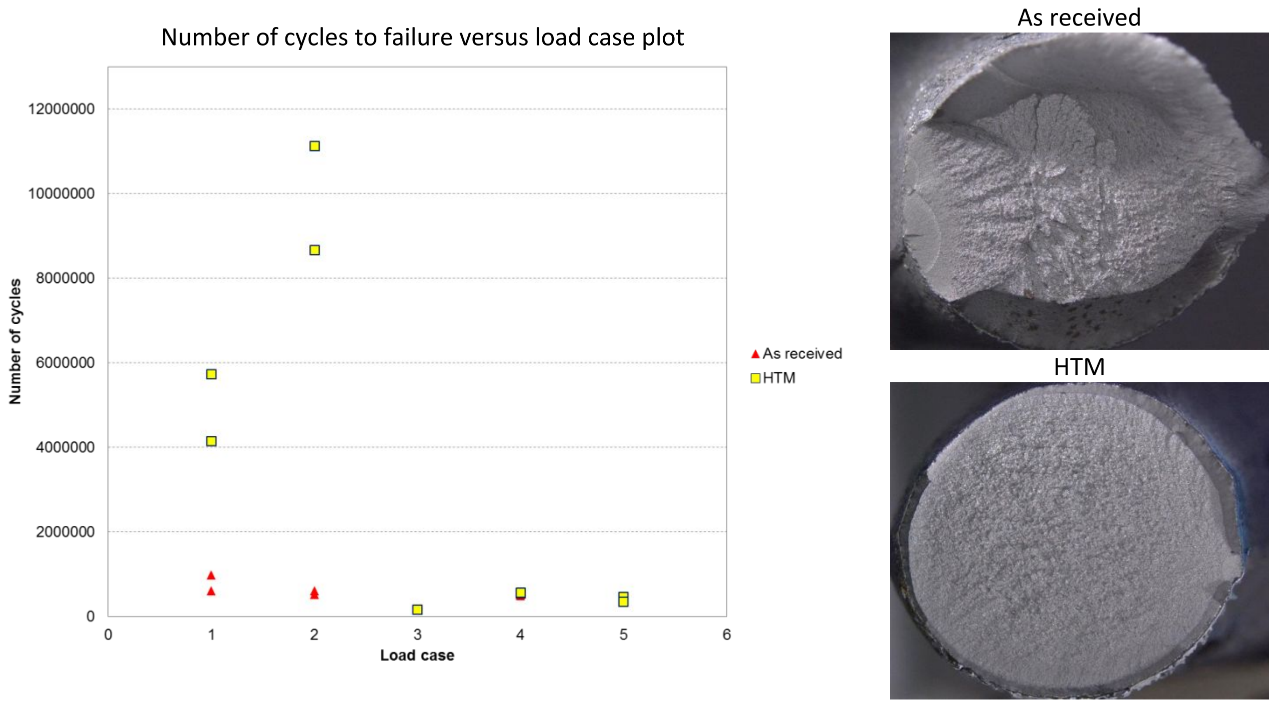

Fig. 4. Difference in fatigue performance and fracture appears between As received and HTM shackles

Fig. 5 depicted the load array along the profile of one of the 3D scanned bow shackles; noticeable is the unequal load distribution between the two legs. The localised areas of high stress not only exceeded the yield strength of the material, but also the ultimate tensile strength thereof. Furthermore the eye section of the leg experiencing higher stress levels revealed localized areas where the material exceeded both yield and ultimate strength compared to the second eye section which does not revealed similar high stress areas. This can be contributed to the inner surface of the bolt hole being tapper, as a result of the shear action during the punching of the bolt hole.

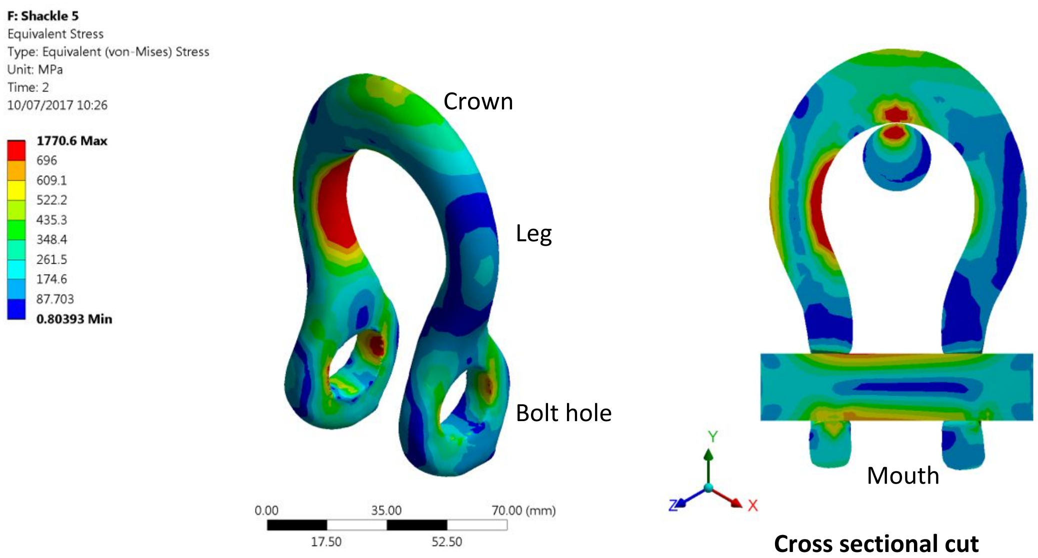

Fig. 5. Colour array indicating load distribution within a bow shackle loaded at 54 kN

In addition Fig. 5 illustrates the typical behaviour of the bow shackle when in tension and the bolt holes of the eye section are misaligned. The attachment point at the crown section is not at the midpoint of the arc of the crown section, but moved towards the side, hence shifting the load distribution more towards the one leg, resulting in an increase in stress levels within that leg. Depending of the magnitude of the stress levels, localised deformation can occur, hence resulting in a further increasing in the degree of unequal loading within the shackle.

The mouth section will tend to open (increase in size) to a point where movement/deformation at the mouth section will be restricted by the nut and bolt head, hence introducing additional loading on the leg that is already experiencing high stress levels. The model confirmed the higher the degree of misalignment between the two bolt holes the higher the unequal load distribution. Therefore, explaining the scattering within fatigue performance data for a specific load case, as an increase in stress levels due to misalignment will result in premature failure of the shackle.

Applying the same loading conditions as used to model the bow shackle to a symmetric straight shackle indicated that the highest stress levels are recorded at the crown section and not within the leg section as in the case of the bow shackle.

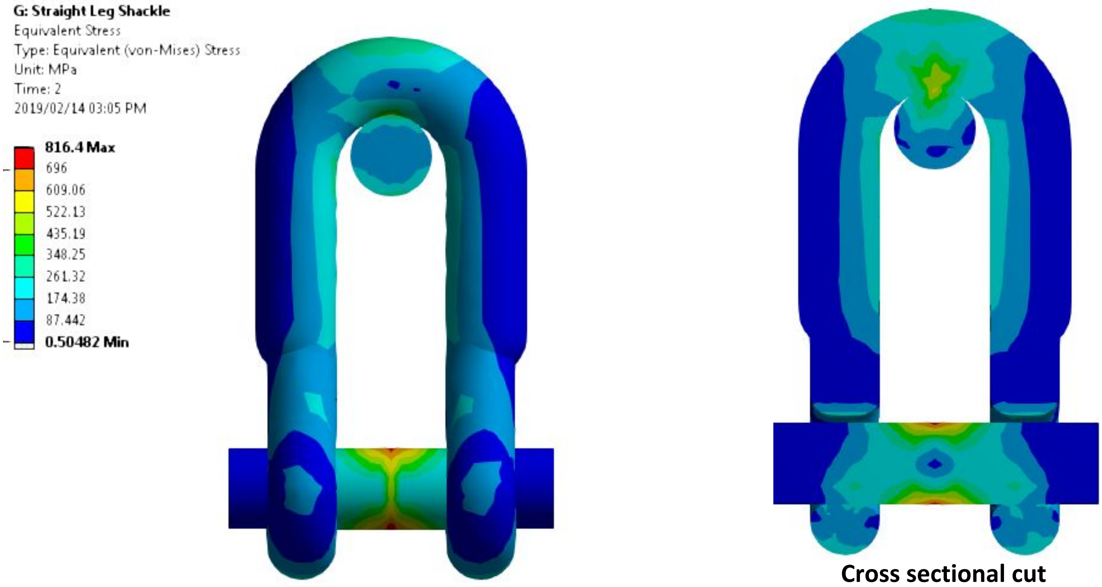

Fig. 5. Colour array indicating load distribution within a symmetric straight shackle loaded at 54 kN

4. CONCLUSION

The fatigue performance of a bow shackle can be improved by altering its microstructure. However, this improvement by metallurgical means is limited to lower load cases, as the curved shape of the leg contributes towards a premature fatigue failure. The leg section is not only subjected to tensile stress when the shackle is under tension, but also to a large degree of bending stresses, as a consequence of its shape. The increase in bending stress with an increase in loading, results in localised overstressing of the material, promoting fatigue crack initiation and propagation.

The fatigue performance is further reduced when misalignment of the bolt holes exist, due to unequal load distribution between the bow shackle legs, which significantly increases the bending stress experience by the leg carrying the higher loading.

Although, the mechanical performance of the bow shackle can be improved by addressing the effect of the taper bolt holes surface and the misalignment thereof by drilling the holes making use of a drill jig versus punching thereof, the effect the curved shape of the legs has on the fatigue performance would remain problematic. By far the greatest improvement in fatigue performance results from design changes, therefore, making use of a straight leg shackle will significantly reduce the bending stresses associated with the curved shaped leg, hence improving both the tensile and fatigue performance of the shackle.

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