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CONDITION MONITORING MOORING CHAINS USING THERMOGRAPHY TECHNIQUE

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ABSTRACT

A new mooring chain condition monitoring technique is studied in this paper by the approach of thermography detection. The research is conducted based on two hypotheses, i.e. (1) the streel material used to make mooring chain has much higher thermal conductivity than that of sea water. Therefore, when the mooring chain is heated, the thermal energy will transmit mostly inside the chain, rather than dispersing in water; (2) the transmission of thermal flow inside the mooring chain is disturbed by the defects. Consequently, the distribution of the temperature in the adjacent area of the defects will be different from the temperature distribution in other areas of the chains. Therefore, the discontinued distribution of the temperature may be an ideal indicator of the defect occurring in the chain. The purpose of the work reported in this paper is to demonstrate these two hypotheses using both numerical simulation and experimental methods, and thus explore an effective approach to the condition monitoring of mooring chains.

NOMENCLATURE

T – time duration
Q – the amount of heat transferred in T
κ – thermal conductivity constant for the material
A – cross sectional area of the material transferring heat
d – thickness of the material
ΔT – the difference in temperature between one side of the material and the other
C – condition monitoring criterion
T_h – the maximum temperature shown in the thermographic picture
T_c – the temperature measured from the other side of the suspected defect

1. INTRODUCTION

Mooring chains are fully submerged in sea water, which is salty and corrosive. In addition, the mooring chains in operation are always subject to large and random forces from wind, waves, tidal currents, tide surge, earthquake and so on. All these challenge the long-term reliability of the mooring chains. According to the survey by the Deepstar®, there have been 107 mooring incidents happen from 73 facilities across the industry from 1997 to 2012 [1], i.e.

- 51 are due to single line failure;
- 9 are because of multiple line failures;
- 38 pre-emptive replacement events;
- 9 are due to severe degradation

Obviously, mooring chain is vulnerable to failure in the practical use. However, its reliability and safety issues are rarely studied before until its safety causes concern recently due to the ageing of North Sea fleet of Oil & Gas drilling platforms [2]. It is believed that most of the aforementioned incidents could be prevented if the defects in the mooring chains can be successfully detected. So far, there are a variety of non-destructive testing techniques have been developed for addressing various structural integrity testing and assessment issues in different fields [3-6]. However, the majority of these available techniques are difficult to be applied to monitoring mooring chains as the mooring chains are full submerged in water. In order to tackle this issue, much effort has been made by the scholars and industrialists in recent years, although a cost-effective and technically reliable mooring chain condition monitoring technique has not been successfully achieved till today. This is because almost all the currently available mooring chain condition monitoring techniques and systems are originally designed for detecting a broken mooring line rather than detecting and monitoring the growth of the defects occurring in it [7-9], with the exception of the ultrasonic guided wave technique developed by TWI [10]. In reality, a defective mooring chain may, but not certainly, lead to the broken of mooring line. For example, ROV inspection has been popularly adopted for inspecting marine structures. It can be equally applied to inspecting mooring chains. However, ROV inspection only provides snapshot of the surface of mooring chains, which could be covered by thick layer of marine lives. Therefore, visual inspection via ROV is unable to provide the operator with reliable information about the actual structural health condition of mooring chains. Moreover, the application of ROV inspection is limited by weather windows and access, it is unlikely to realize the continuous monitoring of the mooring chain. In order to obtain continuous monitoring data from mooring chains, AVT Reliability attempted to use strain gauge to monitor the integrity of mooring chains and applied the devised strain gauge based measurement system to assessing the integrity of the 9 mooring chains installed on a 870,000 barrel oil storage tanker [7]. The novelty of such a system is that it does not directly measure the chain tensions but instead, monitors the stresses in the buoy structural steelwork in reacting those same chain tensions. This has the advantage that the instrumentation can be mounted in a clean dry environment inside the buoy. However, the measured stresses from the buoy structural steelwork are not only dependent on the integrity of mooring chains, but also affected by the motions of the storage tanker and the external loads acting on it. Therefore, the AVT system is effective in detecting a broken mooring line, however ineffective in detecting and monitoring the incipient defects occurring in it. Apart from AVT Reliability, the other companies also develop mooring chain integrity monitoring systems using different techniques. For example, Seatools developed the mooring chain inclination measurement technique [8], Tritech International Ltd developed a multi-beam sonar technique [9], and so on. But they all are for detecting whether the mooring lines are well connected to the floating structures, rather than for detecting the defects in the chains. To tackle this issue, TWI developed an automated ultrasonic guided wave technique for monitoring mooring chains [10]. Laboratory test has shown that such a technique does work in improving the accuracy, consistency and repeatability of inspection results. But it requests to make minimal surface preparation before conducting inspection. However, this is very difficult to implement in the practical application. Additionally, the high cost of the associated robotic delivery system also limits the extensive application of such an ultrasonic guided wave technique. For the aforementioned reasons, a new mooring chain condition monitoring technique is studied below with the aid of thermography technique.

2. NUMERICAL RESEARCH

According to the theory of thermodynamics, the rate of heat flow can be described as [11],

$$\frac{Q}{t} = \frac{\kappa A}{d} \Delta T \quad (1)$$

From (1), it can be inferred that

- since the thermal conductivity κ for steel is 46 Watts/meter$-^{o}$C, which is much higher than the thermal conductivity of water (i.e. κ for water is only 0.58 Watts/meter$-^{o}$C), the heat flow will be transferred much faster in steel than in water. Accordingly, when the steel mooring chain is heated from one end, the majority of heat flow will be transferred inside the steelwork of the chain rather than being dissipated in the water around it;
- equation (1) shows that the cross sectional area A is inversely proportional to the temperature difference ΔT . That means when the same amount of heat is transferred inside the chain, the defect resulted change in the cross sectional area A will be indicated by the change in temperature or temperature distribution. In the meantime, the heat flow will be transferred automatically along the path which has smaller thermal resistance.

If the above two hypotheses are true, then the integrity of the mooring chain can be detected via observing the distribution of mooring chain temperature. In other words, the discontinuity in temperature distribution may indicate the presence of defect in mooring chain. In order to demonstrate these two hypotheses, numerical research was conducted first with the aid of commercial software ANSYS 15. The meshed mooring chains are shown in Figure 1. Where, the chains are made of steel and finer meshes are used in the vicinity areas of the defect for obtaining more accurate calculation result. In the numerical calculations, both environmental temperature 22 Celsius and heating temperature 300 Celsius are specified in the steady state thermal column. The convection film coefficient is also defined in this section. The value is taken as 22 W/m^{2}C. When the heating temperature is applied at one end of the mooring chains while the other end is fixed and no temperature is applied, the numerical calculation results for a partially cracked mooring chain are graphically shown in Figure 2.

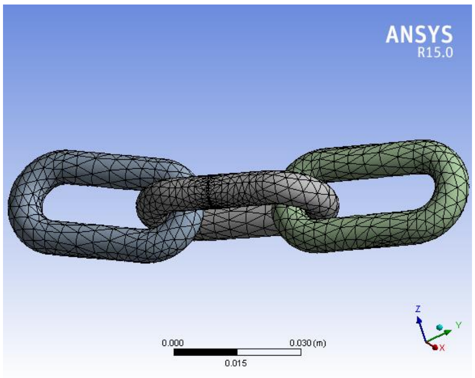


Figure 1. Meshes of the mooring chains

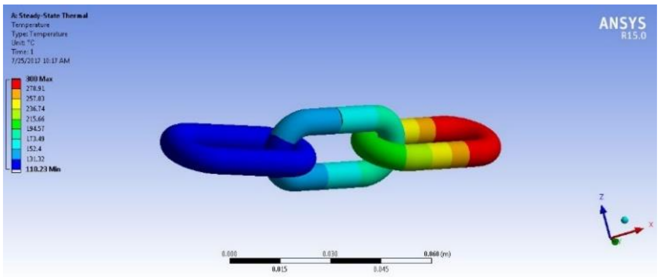


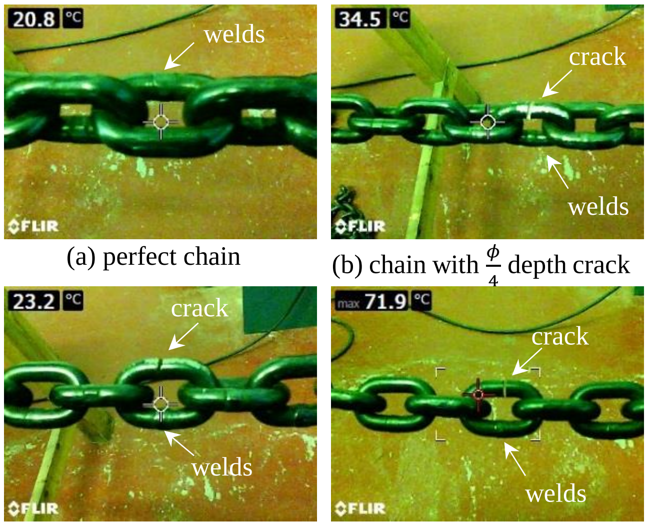
Figure 2. Numerical result obtained when a partially cracked mooring chain is heated from one end

From Figure 2, it is found that

- the discontinuity of the temperature observed from the upper part of the defective mooring chain proves that the defect in the mooring chain does disturb the transfer of heat flow, thus may cause visible temperature difference in the vicinity area of the defect;
- the asymmetric distribution of the temperatures of the upper and lower parts of the defective mooring chain proves that heat flow is more easily to be transferred along the path that has smaller thermal resistance;
- although in the numerical simulation, the mooring chain is assumed to be placed in air rather in water, the visible temperature differences prove that when the steel mooring chain is heated from one end, the majority of heat flow will be transferred inside the steelwork of the chain rather than being dissipated outside the chain as the thermal conductivities of air and water are similar and much smaller than that of steel mooring chain; and
- moreover, the profile of the temperature distribution around the defect indicates the size of the defect.

3. EXPERIMENTAL RESEARCH

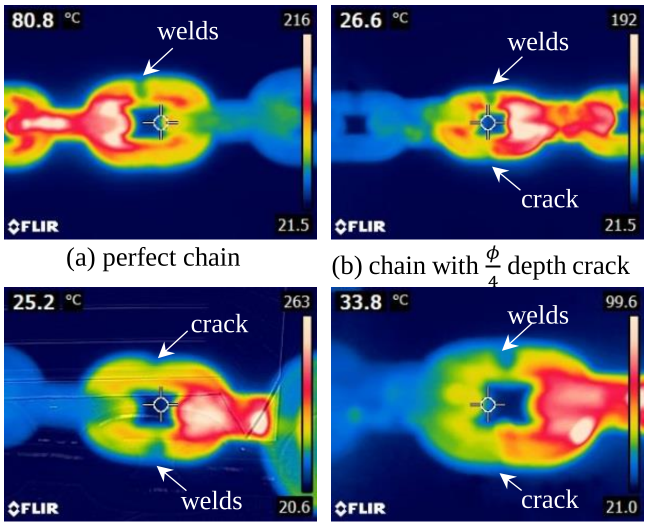
In order to physically demonstrate the interesting findings observed from numerical research, experimental research was conducted in laboratory. Both perfect chains and the defective chains with different sizes of cracks are shown in Figure 3.



(a) perfect chain (b) chain with $\frac{\phi}{4}$ depth crack
(c) chain with $\frac{\phi}{2}$ depth crack (d) chain with through crack

Figure 3. Mooring chains used in the experiments.

In the experiment, the influences of the crack on the temperature distribution of the chain are investigated through heating the chain of interest from one end. The corresponding experimental results are shown in Figure 4.



(a) perfect chain (b) chain with $\frac{\phi}{4}$ depth crack
(c) chain with $\frac{\phi}{2}$ depth crack (d) chain with through crack

Figure 4. Experimental results obtained when the chains are heated from one end

From Figure 4, it is found that when the mooring chain is perfect and has no any defect, the temperature is distributed evenly and smoothly over the chain except at welds, where the temperature is obviously smaller than in others due to the much lower thermal conductivity of the welding material. But when a crack is present in the chain, the even distribution of the temperature over the chain will be discontinued. Consequently, a discontinued profile can be observed from the cracking area in the thermal image. Moreover, it is found that the larger the size of the crack, the more obvious the discontinuity tends to be. This is because the air or water in the clearance of the crack has lower thermal conductivity than that of the mooring chain material. Therefore, the air or water temperature in the crack clearance is lower than that of the steelwork of the chain. From such an observation, it can be inferred that a partial through crack can partially stop the transfer of heat flow, although the heat flow is still able to be transferred through the un-cracked section. But when the crack continues to propagate and finally becomes a full through crack in the end, the transfer of heat flow will be significantly limited by the crack. In this worst case, the heat flow in the cracking area is transferred only via the air or water in the clearance of the full through crack. In general, from these experimental results, it can be concluded that the crack occurring in the mooring chain can be readily detected using thermographic technique. But the quantitative assessment of the crack is not easy to achieve directly from the observation of the thermo-pictures. To address this issue, a quantitative assessment method is developed in the following by using the temperature reading function of the thermographic camera. In addition, it is noticed that there is a temperature value displayed at the top left of the picture, such as 80.8 ^{o}C in Figure 4a, 26.6 ^{o}C in Figure 4b, 25.2 ^{o}C in Figure 4c, and 33.8 ^{o}C in Figure 4d. These values indicate the temperatures at the positions located by the circle with a cross. With the aid of this special temperature reading function provided by the thermal camera, the temperature at any position in the thermal image can be readily obtained. Then, the temperatures at two specific positions are measured for developing the quantitative assessment criterion. One is the temperature T_h measured at the heating source position, another is the temperature T_c measured at the other side of the crack. Since the temperature at the heating source position is the highest temperature in the thermal image, the value of T_h is usually the maximum value shown in the grey scale of the image, i.e. $T_h = 216\ ^{o}C$ for Figure 4a, 192 ^{o}C for Figure 4b, 263 ^{o}C for Figure 4c, and 99.6 ^{o}C for Figure 4d. Therefore, in fact T_c is the only value that needs to be measured by moving the circle with a cross to the other side of the crack. Once the value of T_c is obtained, the following quantitative assessment criterion can be calculated, i.e.

$$C = \frac{T_h - T_c}{T_h} \times 100\% \qquad (2)$$

As the larger crack will limit more of the transfer of heat flow it will result in a lower value of T_c thus a larger value of criterion C at a certain value of T_h. Therefore, the criterion C can be used to quantitatively assess the size of a transverse crack occurring in the mooring chain. In the experiment, the values of T_c have been read from the images shown in Figure 4. They are $T_c = 97\ ^{o}C$ for Figure 4a, 85 ^{o}C for Figure 4b, 111.5 ^{o}C for Figure 4c, and 40 ^{o}C for Figure 4d. Substitute the values of T_h and T_c into (2), the criterion C is calculated and the results are shown in Figure 5.

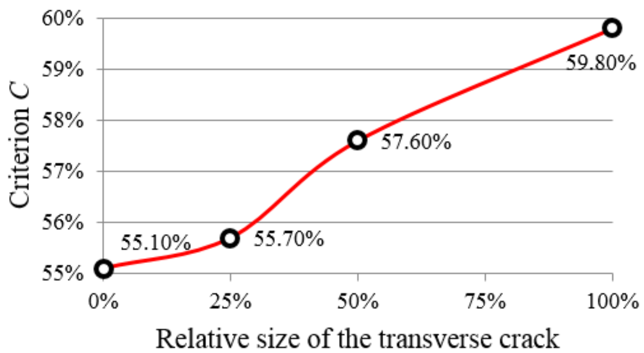


Figure 5. Quantitative assessment of the crack occurring in the mooring chain

From Figure 5, it is clearly seen that as expected, the value of criterion C does increase gradually with the increasing depth of the crack. This fully demonstrates that the proposed quantitative evaluation method does work in assessing the crack occurring in the mooring chain.

4. CONCLUSIONS

In order to develop an effective and reliable for condition monitoring mooring chains, both numerical and experimental researches are conducted in the paper to investigate the potential of thermography technique in detecting transverse cracks occurring in mooring chains. From the work reported above, the following conclusions can be drawn:

(1) When the mooring chain is perfect in structural integrity, the temperature is smoothly distributed over the chain except at welds, where the temperature is smaller than in other chain parts due to the lower thermal conductivity of welding materials in comparison of that of the steel material of mooring chain;
(2) The proposed quantitative evaluation method can successfully predict the presence and growth of the crack when the chain is heated from only one end;
(3) Both numerical and experimental researches have demonstrated that thermography technique does have potential to be applied to condition monitoring mooring chains. However, further research is still required to develop an appropriate method to heat the mooring chain in a completely wet environment.

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