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STRUCTURAL INTEGRITY ASSESSMENT OF MARITIME TRANSPORT EQUIPMENT

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ABSTRACT

Structural integrity assessment is the study of the safe design and assessment of components and structures under loads, and has become increasingly important in engineering design. The technology and applications of structural integrity widely range from transportation, oil and gas, power generation to petrochemical, nuclear sectors, etc. In this paper, the character of structural integrity assessment in the maritime field is discussed, the latest approach and techniques are classified in three sub-topics, damage diagnosis, damage prognosis & maintenance strategy and then illustrated using a few practical studies. Finally, the future challenges introduced by new material, new exploitation field and new technology, i.e., IOT, big data, etc., are discussed and the potential development of structural integrity assessment in maritime industry is explored.

Keywords: transport equipment, structural integrity, deep sea, virtual reality, maintenance, big data

INTRODUCTION

The maritime transport plays an important role in facilitating international trade and maintaining global economy. Typical equipment deployed for maritime transport include vessels, pipelines, cranes among others. Those transport equipment grow in terms of size, capacity and complexity accompanying continuous development of maritime transport. It is essential to ensure the safety and performance of those equipment in order to maintain a safe, reliable and effective maritime transport.

Structural integrity is the ability of a structure or a component to withstand a designed service load, resisting structural failure due to aging factors, such as fatigue, fracture and corrosion, etc. The research on structural integrity aims to produce items that will not only function adequately for their designed purposes, but also function for a desired service life. In this regard, the ultimate goal of the research on structural integrity of maritime transport equipment is to maintain their safety and reliability. Maritime transport equipment are in general welded, thin walled metallic structures. Welding and other secondary treatments would introduce flaws into material in forms of porosity, constituent particles, inclusions. When they are subjected to cyclic environmental and operational loads together with corrosive sea water, fatigue and corrosion damage are typically resulted, such as cracks, pits, metal loss, etc. The existence of those damages will jeopardize structural integrity of equipment and cause catastrophic consequence under an extreme situation. Therefore, the research on structural integrity of maritime transport equipment always starts with damage diagnosis, proceeds with damage prognosis and ends with maintenance decision making, see Fig.1.

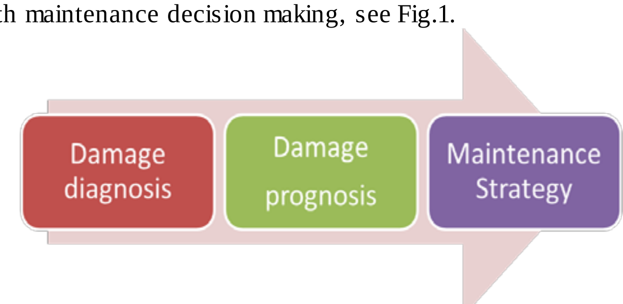

Fig. 1 Three sub-topics of research on structural integrity

In the following sections, those three sub-topics will be discussed separately and future tendency of structural integrity studies is prospected and discussed.

DAMAGE DIAGNOSIS

Damage diagnosis is to detect and characterize damage occurring to the structure with aim to answer following questions:

- Whether is the structure / component damaged?

- Where is the damage located?
- What type of damage is it?
- What is the dimension /extent of damage?

Those information can be acquired through regular inspection and measurement. A wide range of methods can be deployed in order to identify the damage with varying expense and accuracy, ranging from simple visual inspection to advanced non-destructive techniques (NDTs), such as ultrasonic testing, eddy currents, acoustic emission and microwaves, etc. Normally, inspection and measurement are done manually. In the case of inaccessibility, such as internal inspection of pipeline system, an intelligent pig equipped with various NDTs can be deployed, such as a magnetic flux leakage (MFL) pig shown in Fig.2, which is typically used for metal loss inspection of pipeline.

Fig.2 A magnetic flux leakage (MFL) pig[1]

To date, advanced composite material, such as Carbon Fiber Reinforced Plastics (CFRP), has been introduced into maritime industry and used as construction and / or reinforcement material. CFRP and the steel plate are typically bonded together through glue/ adhesive. Since their material property differs significantly, traditional NDTs valid for pure steel may not function well at presence of CFRP, thus a combined or hybrid method could be demanded in order to overcome some inherent weaknesses of traditional NDTs[2]. For instance, Eddy current is sensitive to surface and sub-surface damage of conductive material. But the conductivity of CFRP is poor and in case of a CFRP-steel structure, as shown in Fig.3, a crack within the steel cannot be detected as usual. Considering that the eddy current produces heat and CFRP is thermal sensitive, eddy current pulsed thermography (ECPT) would be a feasible substitute, as indicated in Fig.4 [2].

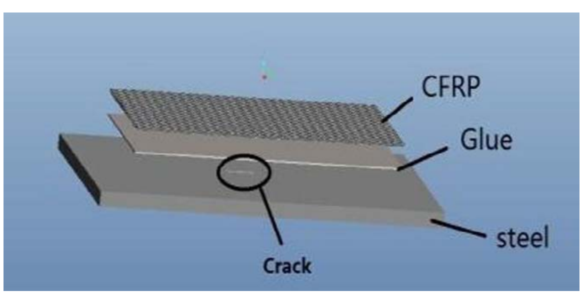

Fig.3 Diagram of damage location, showing the CFRP layer, the glue layer and the steel substrate[2].

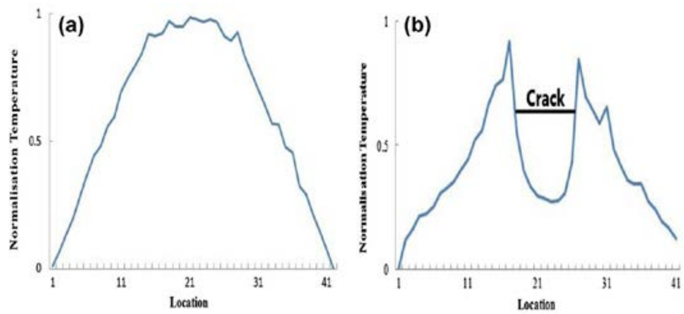

Fig.4 Transient thermal behavior after 200 ms of heating: (a) intact and (b) cracked model results[2]

In practical application, all those NDT methods are generally range-limited considering demanded power. And those methods could be expensive to implement on a large scale due to the associated labor and wiring costs. In this respect, a dual-substrate antenna sensor has potential to service the structural healthy monitoring in practice better considering that it can realize passive and wireless monitoring of cracks on FRP-strengthened steel structures [3].

DAMAGE PROGNOSIS

Once the damage is identified, the effect of damage on structural capacity can be quantified, the evolution of damage and the remaining useful life of the structure can be predicted through experiments, numerical simulation as well as analytical calculation[4-5].

Experimental research is the most reliable method to trace the evolution of damage and evaluate the residual strength of a damaged structure. However, relatively high cost associated with experiments hinders its wide application in the reality[6-8].

Numerical simulation, such as Finite Element Analysis (FEA), has been well-established and become a suitable alternative of expensive experimental studies. It should be noted that the idealization of modeling is inherent with FEA and the reasonability of FEA relies to a large extent on the expertise of a user. Therefore, a FEA model needs to be validated through measurement or test. Moreover, FEA is in general time-consuming and thus less practical from daily operation perspective.

Analytical method is a typically semi-theoretical, semi-empirical approach. The most attractive character of an analytical method is its rapidity- the work can be done in minutes even seconds. However, an accurate analytical result is not achievable by hand calculation unless in a very simple and specific situation[9]. A real structure cannot satisfy those pre-conditions in a sense of multiple materials, loads and boundary conditions. In this case, a rational analytical approach can be developed exclusively based on extensive numerical studies, particularly FEA [10-13].

In those regards, a combination of measurement(test), FEA and analytical method may provide us with a fast, economic, and sufficiently accurate assessment. For instance, offshore pipeline typically suffers from service induced damage, i.e., cracks, dents, pits / metal losses. It is essential to quantify the adverse effects of damage on the residual ultimate strength of offshore pipelines in order to guide damage tolerance based design [5-8]. Firstly, a preliminary FEA was performed to determine the loading capacity of the test machine and set up a reasonable test plan as shown in Fig.5 [6]. Thereafter, a series of large scale pipeline tests were conducted accounting for different damages and their combination, referring to Fig.6.

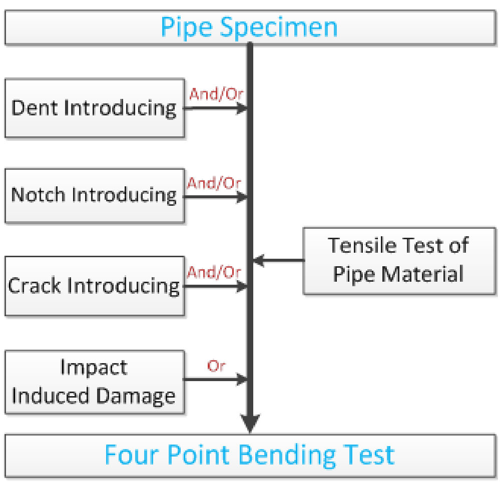

Fig.5 Pipeline test plan[6]

Fig.6 Left: Introduction of dents through quasi-static indentation; Right: Four point bending test [7].

The preliminary FEA model was then adapted to the actual test profile and the FEA result was validated (or invalidated) by the test data [7-8]. Comparative studies indicated a sound FEA model in terms that the predicted displacement and failure mode by FEA matched well with the test result, see Fig.7.

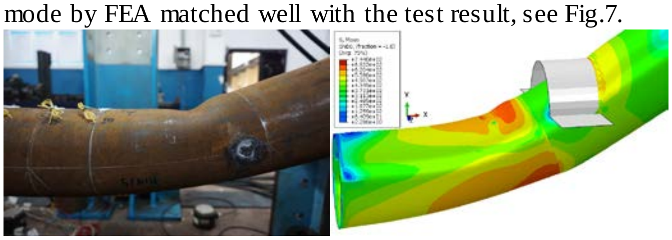

Fig. 7 Comparison between test (Left) and FEA (Right) [7]

After validation of FEA simulation, a series of parametric studies were carried out in order to develop a rational analytical model. Fig. 8 showed some numerical results of notched pipelines[8], the parameter under concern was the normalized depth of notch. The corresponding analytical formula to predict the residual ultimate strength of notched pipeline was given in Eq. 1. It can be conveniently deployed to predict the residual strength of pipeline suffering from metal loss.

$$\frac{M_{cr}}{M_i} = 1 - 1.4\left(\lambda_l \frac{d_m}{t}\right)^{0.9} \left(\lambda_w\right)^{0.25} \qquad (1)$$

Where, M_{cr} and M_i meant the residual and ultimate bending moment of a notched and an intact pipeline respectively. λ_l, d_m/t, λ_w were dimensionless length, depth and width of the metal loss (notch), t was the pipe thickness.

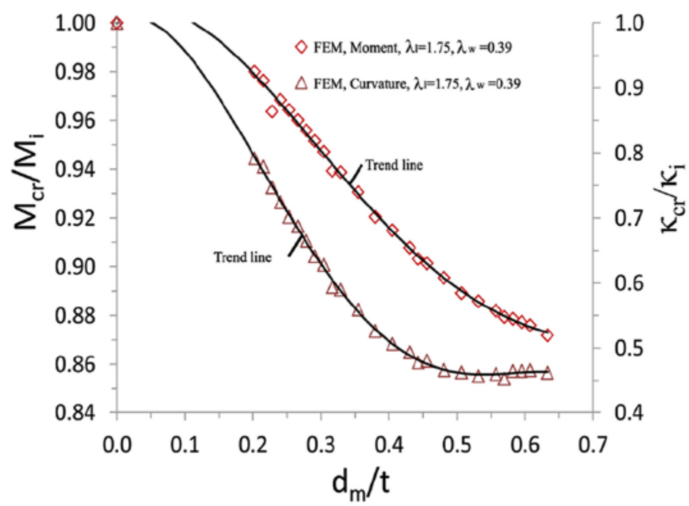

Fig.8 Effect notch depth on the residual strength of the pipe in terms of residual bending capacity and critical curvature[8]

MAINTENANCE DECISION MAKING

Maintenance is an important aspect of the long-term structural integrity management of engineering structures. The validity of a maintenance plan primarily depends on correct prediction of the remaining service life of the structure and evaluation of associated uncertainties. In the case of maritime transport equipment, inspection and maintenance are performed traditionally on a periodic basis instead of conditional basis. Since maintenance contributes to the life cost of the structure considerably, a rational maintenance strategy needs be established based on structural reliability analyses in order to reduce associated cost but maintain sufficient structural safety[14].

For instance, the accumulated fatigue damage is normally assessed through S-N curve based method. This approach is simple and easily executable but with an apparent drawback - the growth of fatigue crack cannot be accounted properly. An alternative method is to relate the number of stress cycles to crack size based on fracture mechanics (FM) theory[15-19]. A framework of maintenance management could then be developed accounting for inspection and repair, where the probability of damage detection (POD) can be considered and the updated reliability after inspection can be calculated using the Bayesian approach[15-19].

A limitation of FM based approach is that the statistical information of the parameters used in the FM formulation is generally not well established, such as the stress intensity factor. Comparatively, statistical information on S–N curves for different structural details are relatively well known. In order to overcome such limitation, the FM formulation can be firstly calibrated using S–N curves and Palmgren–Miner's rule and the calibrated FM formulation would be deployed to update the reliability according to the inspection results using the Bayesian approach[20-21], see Fig.9 & 10 respectively. In both figures, the transverse axis is time in years, and the vertical axis is reliability (safety) index. The feasibility of an inspection plan can be judged based on the comparison between the updated reliability and the target reliability index[19-21].

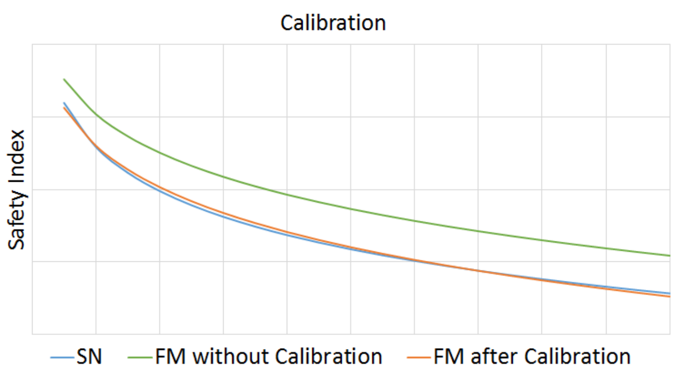

Fig. 9. Calibration of FM formulation using S–N curves and Palmgren -Miner's rule [20]

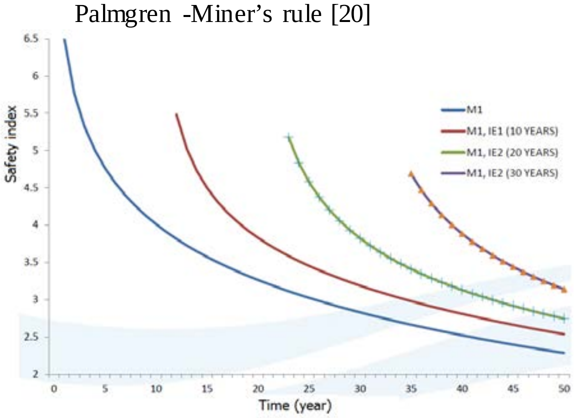

Fig. 10 Updating the reliability according to multi-inspection results using the Bayesian approach[21]

Maintenance tasks are constrained by the accessibility. Cranes are large scale mechanical equipment and widely used for port and maritime operation. Statistical data showed that 95% of the fatigue failure occurs to the boom structures. and the most fatigue-sensitive component of crane is located at tubular joint of top arms, as shown in Fig. 11. This critical location is hardly accessed and maintained, and on-situ measurement is too expensive and hardly available in practice[22]. In this respect, virtual reality can be deployed to represent actual operation and produce real time data by applying Multi-Body Dynamic(MBD) analysis, see fig. 12 and 13 [23]. Actual fatigue damage can be assessed and predicted by coupling MBD and FEA approach in order to guide maintenance of the crane and improve its fatigue design.

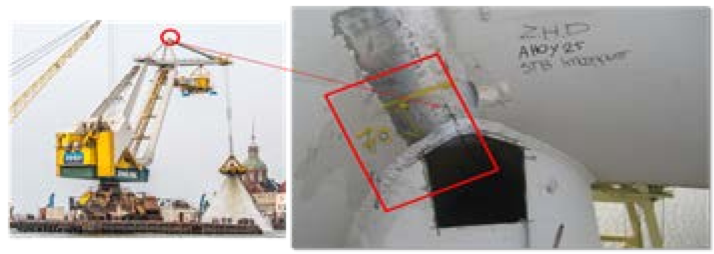

Fig. 11. A detected crack on a lemniscate crane[22]

Fig.12 A floating lemniscate crane (Left: Picture; Right: Virtual MBD model)[23]

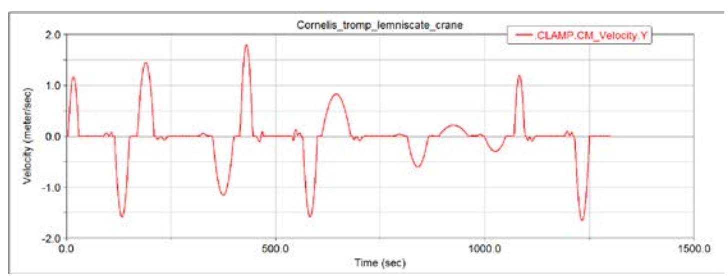

Fig.13. Virtual reality based hoisting simulation of the lemniscate crane [23]

TENDENCY OF DEVELOPMENT

To date, structural integrity assessment of maritime transport equipment is confronted with new challenges and opportunities introduced by new material, new exploitation environment and new technology among others.

Traditional construction material for transport equipment is mild steel. In recent years, high tensile strength (HTS) steel has been widely applied in maritime industry in order to reduce weight and maintain sufficient strength and stiffness. However, the fatigue strength of HTS steel in terms of the fracture toughness Kca is in general lower than that of mild steel. It poses new difficulty and challenge on the design and manufacture of welded HTS thick-sectional joints.

Although the current design codes are well established in providing the requirements on material fracture toughness to prevent crack initiation, in most scenarios, crack initiation is unlikely to be prevented in any absolute sense considering current fabrication qualities, workmanship as well as severe service conditions. Therefore, it is considered a practical approach for the designer to demand crack arrest-ability of the steel which acts as the second safety guard line.

It is essential to understand the fundamental behavior of HTS plates in fracturing and identify the relationship between material strength, thickness and Kca to correctly evaluate the crack arrest-ability of thick HTS steel plates and enhance the structural safety of large maritime transport equipment. Some preliminary studies have indicated the possibility to establish a FEA procedure to simulate the crack driving force and evaluate the crack arrest-ability of thick higher tensile steel plates [24].

Composite Repair System (CRS) is an advanced maintenance technique in pipeline industry, where Fiber Reinforcement Polymer (FRP) is typically used. Although FRP reinforcement technique has been widely used for repair of metallic structures, most of them addressed load-carrying components instead of transferring ones, such as pipelines[25]. A significant difference between them is that a through crack is generally not allowed for the latter since a through crack means leakage and the leakage of pipeline would result in a catastrophic consequence, like fire or explosion of oil /gas.

There has been extensive studies on either residual strength of cracked metallic pipelines or failure mechanism of FRP. However, in the presence of FRP bonded with cracked steel through adhesive, the stress status at crack tip become more complicated at interface of multi-material, the failure mechanism of the system is not clear, and the durability of CRS is hardly measureable and predictable. Thus a systemic research is demanded in order to unveil the mystery and thereafter guide the design of CRS for metallic pipeline.

With globally increasing demand on energy, oil and gas tend to be explored at water depth beyond 3000m as shown in fig.14[26]. It was named ultra-deep water exploitation.

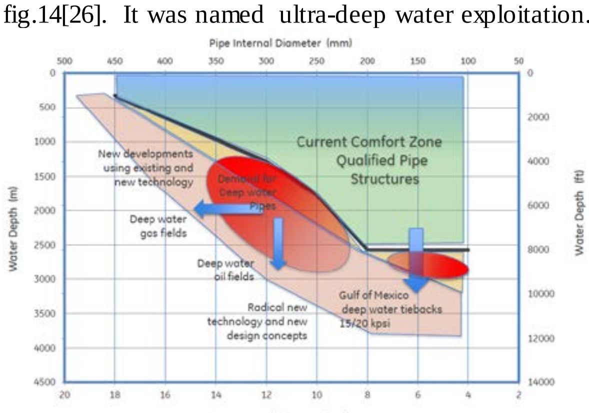

Fig.14 Market demand and current status[26]

This new environment poses extremely high hydrostatic pressure on the transport equipment – flexible riser, a pipelike equipment with multiple layers for better flexibility. Such an excessive external pressure would cause collapse of the riser. Up to now, there has been no well-established method available to predict this collapse associated pressure value in ultra-deep water, leading to a too conservative design of riser in terms of heavier and more costly material[27]. Therefore, it is essential to conduct further research in order to develop an effective method for prediction of this critical pressure and guide the anti-collapse design of flexible risers. This design makes use of information on the circumstances in which the equipment will operate and services ultra- deep water exploitation, it is called evidence based design as well[28].

In the previous section, the maintenance decision making has been discussed with more attention paid to a localized damage and its propagation. But in the reality, multiple damage can occur simultaneously. Moreover, a transport equipment is a system consisting of multiple subsystem or components. The failure mode and rate of each subsystem/ component are generally different and can be interdependent. In order to improve the effectiveness of the maintenance, a predictive maintenance model would be a smart solution. With the aid of such a model, the equipment can "foresee" the time to fix sub-system / components before they actually break, saving costs and increasing safety [28-29].

Nowadays, the rapid development of the Internet, Internet of Things(IOT) and cloud computing promotes explosive growth of data in almost every industrial and commercial areas[30]. The abundance of data can be converted into useful information by applying big data technology. As a result, it is possible to obtain the underlying laws and values implied in the data, reveal complex relationships between different variables, and finally optimize operation and maintenance of the transport equipment[31]. For instance, a predictive maintenance plan considering offshore wind can be established based on the big data analytics[32]. And an optimization model of maritime operation can be established to determine the optimal ship type and capacity, the sailing route and speed, drag power, etc., see Fig. 15.

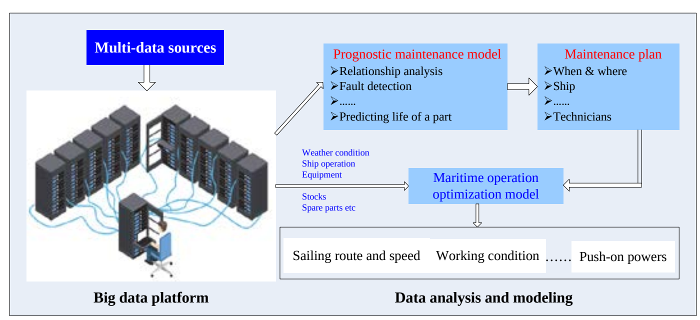

Fig.15 Development of a predictive maintenance plan based on big data technology

SUMMARY

Maritime transport equipment is a system consisting of multiple sub-systems or components. The failure modes and failure rates of subsystems / components are generally different but correlated and interdependent. It means that the failure of one component would induce subsequent failure of other components and finally endanger the safety and functionality of the whole system.

On the one hand, introduction of new material and new exploitation area will bring about new, unknown failure mechanism. It is important to understand it and take proper measures to prevent it or mitigate the consequence. This part of work generally belongs to the structural integrity assessment at component level, since the interaction between sub-systems is not taken into account.

On the other hand, the maintenance strategy of the equipment should be made on a system level simply because it is not economical and effective to shut down the system per repair of each component. Traditional maintenance of maritime transport equipment is time based instead of condition based. One main reason was the lack of data or information on the real time condition of the system. With the development of IOT and big data analytics, it has become possible to collect, analyze abundant data and retrieve useful information and set up a prediction based, integrated maintenance plan.

As a summary, a cross-disciplinary and integrated approach is demanded in order to develop a rational structural integrity assessment of maritime transport equipment. Herein, “cross-disciplinary” means the associated studies shall cover such fields as material, maritime, mechanical, computing and automatic control, among others. “integrated” means the associated studies shall bridge failure mechanism at component level and maintenance decision making at system level properly.

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