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Fatigue Reliability of Marine Structures, from the *Alexander Kielland* Accident to Life Cycle Assessment

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Development of reliability-based management of inspection, monitoring, maintenance and repair (IMMR) of various types of offshore structures is described, with a focus on management of hull damage due to crack growth. Operational experiences are summarized, and recent developments relating to fatigue loading, resistance and reliability approaches are described. The interrelation between design criteria and IMMR is emphasized. It is shown how design for robustness—in terms of residual fatigue life and residual overload capacity, choice of inspection method and scheduling as well as repair strategy—needs to be implemented so as to obtain an acceptable risk for various types of offshore structures.

INTRODUCTION

The first scientific accounts of fatigue failures date back to the 1850s. Famous are the German railway engineer Wöhler's works in the period 1847–70. In the following 100 years, various fatigue failures took place in metal structures. The accounts of these accidents were disseminated and also inspired authors. Kipling described a fatigue failure of a propeller shaft in *Bread Upon Waters* in 1895. Particularly interesting is Nevil Shute's prophetic novel *No Highway*, describing fatigue failures of airplanes; this was published in 1948, five years before the fatigue-induced losses of Comet airplanes. Research on the fatigue behaviour of welded structures was initiated after ship and bridge fatigue damages in the 1950s and '60s. Textbooks appearing in the '60s documented that fatigue analysis was becoming a mature discipline (e.g. Gurney, 1968). Even though fatigue has been documented as a phenomenon for decades, history shows that it had to be rediscovered several times after the occurrence of fatigue failures. The main cause of failures is found to be gross errors—i.e. complete absence of fatigue design check, lack of awareness of dynamic load effect phenomena, bad design detailing, gross fabrication defects, nonredundant structure, as well as lack of or deficient inspection (e.g. Moan, 2005). Fatigue is an important consideration for structures in areas with more or less continuous storm loading, such as offshore structures in the North Sea and ships in worldwide operation, and especially for dynamically sensitive structures and welded joints with high stress concentration. Fatigue proneness increases with the use of materials with higher static strength in welded structures since the fatigue capacity does not increase.

The first rules for offshore structures appeared around 1970 and included fatigue requirements, which were later refined, especially after the fatigue-induced total losses of the jack-up *Ranger I* and semisubmersible *Alexander L. Kielland* in 1979 and 1980, respectively. Cracks have been known to occur in steel ships for decades. While fatigue was considered for some ship types, such as LNG tankers and container vessels in the 1970s, and FPSO in response to the experiences with *Petrojarl I* (Bach-Gansmo et al., 1987), it was not until the 1990s that fatigue criteria were explicitly introduced for ships in general. Actually IACS introduced its fatigue design procedure for ships in 1999 (IACS, 1999). The new fatigue design rules were introduced as a response especially to the significant fatigue problems experienced by side longitudinals of 2- to 5-year-old VLCC tankers in the Alaska-California trade (e.g. Sucharski, 1997). Current design approaches for offshore structures are implemented in codes issued by ISO 19900 (1994), API (1993/97) and NORSOK N-001(1998), as well as various classification societies. Fatigue design and inspection practice for ships has been established by various classification societies, most recently by the IACS efforts (JBP, 2005; JTP, 2005) Fatigue strength is commonly described by SN data. Fracture mechanics methods have been adopted to assess more accurately the different stages of crack growth, including calculation of residual fatigue life beyond the through thickness crack, which is normally defined as fatigue failure. Such detailed information about crack propagation is also required to plan inspections and repair. A particular issue is the link between fatigue and ultimate failure of components, as well as the implication of abnormal fatigue failure in progressive failure criteria, in terms of the so-called Accidental Collapse Limit State (ALS), which is motivated by the design philosophy that "small damages, which inevitably occur, should not cause disproportionate consequences."

In the last 10 to 15 years, Inspection, Monitoring and Maintenance and Repair (IMMR) are increasingly focused on fatigue and other degradation phenomena. But their effect on reliability depends upon the quality of inspection, e.g., in terms of detectability vs. size of the damage, as well as the time required for repair. Hence, an inspection and repair measure can contribute to safety only when there is a certain structural damage tolerance. This implies an interrelation between design criteria (fatigue life, damage tolerance) and the inspection and repair criteria. While the initial IMMR plan is made at the design stage, it is updated depending upon findings during inspections. Such a condition assessment is especially important in connection with extension of the service life of marine structures. For instance, information about inspections resulting in no crack detection at the late stages of service life implies a higher reliability than anticipated (Moan, 2000).

The offshore industry early on recognized that uncertainties, load effects and resistances should be accounted for in making

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