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Estimation on structural availability of slender beam's yield strength, using structural failure model based on the Poisson approximation

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ABSTRACT

This paper presents a new approach to the structural availability quantification of a slender beam element affected by external random loads with a special focus on yield strength. The proposed method introduces the concept of structural availability, which is intrinsically identical to the concept of operational availability in system reliability engineering. Structural availability is formulated with structural failure and repair models. The failure model is determined based on failure probability and the Poisson approximation. In applying the structural availability method to design, it is possible to quantitatively measure features related to the operation and maintenance of structures and to identify cost-effective design options. To understand feasibility levels of structural availability, two cases based on actual design data are examined using the proposed method. The case study results illustrate not only processes of quantifying the structural availability of a beam element but also the cost-effectiveness evaluations on specific design options.

1. Introduction

Ship structural design methods have been considerably improved through a number of studies, and improvements in structural safety have in turn been achieved (Beghin, 2013; McNatt et al., 2013). One representative method is the structural rules of the Classification Society, which manages the majority of structural design variables in a deterministic manner. This deterministic method, i.e. rule-based method, mainly proposes the minimum requirements that each design case must satisfy. In recent years, in the interest of further design optimization, the risk-based design (Papanikolaou, 2009) approach has been studied, and related research is actively underway.

Regarding risk-based design, a probabilistic approach to managing uncertainties of design variables is essential. Structural reliability analysis methods have been developed since the 1950s (Freudenthal, 1956), and through such methods, structural safety can be calculated in a probabilistic manner. From structural reliability values, it is possible to quantitatively consider variations in structural safety levels followed by design changes. Nevertheless, the method still presents shortcomings in terms of risk-based design: it is difficult to account for probable effects of the maintenance of failure-repair systems and cost-effectiveness issues in a quantitative manner. Recently, several studies on the risk-based design of hull girder structures have been conducted using the failure probability derived from structural reliability analysis (e.g., Skjong and Bitner-Gregersen, 2002; IMO, 2006). However, such studies still use the rule-based design framework, as they are based on partial safety factors and don't consider the effects of structural maintenance. Further, existing research on the risk-based design of local members of ship structures is currently insufficient.

In the petrochemical, chemical, and power plant industries, production (or operational) availability has been used to show the extent to which a system approaches stable operations without production loss. By using the availability, more practical design optimizations based on estimations of production levels and evaluations of maintenance policies are achievable. In turn, the availability concept is applicable to the risk-based design of ship structures, and thus, structural maintenance effects can be quantitatively considered throughout the design process. Juan et al. (2011) examined the structural availability of a small truss structure by assuming that the failure model of a truss element follows a Weibull distribution without failure probability calculations. Hess (2003) and Knight et al. (2015) also examined the structural availability related to fatigue cracks in naval ship structures, whereby a failure model based not on failure probability but on a binomial distribution assumption was applied.

Regarding the yield strength of a slender beam element subjected to random external loads, this study proposes a method of structural

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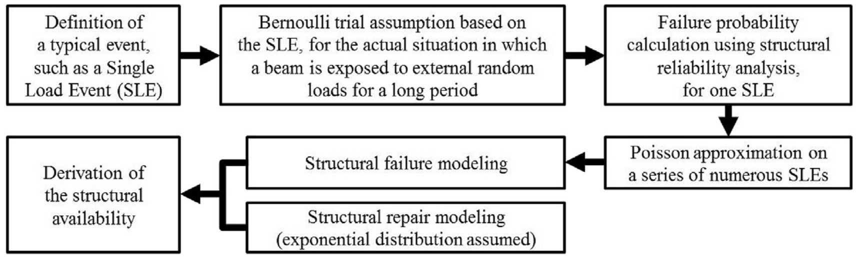

Fig. 1. Outline of structural availability quantification method.

availability quantification based on a new perspective. The new method presented in this article first shows that it is possible to define the probabilistic failure model of a structural member based on the probability of failure derived from structural reliability analysis and the Poisson approximation. Second, this study specifies how to quantify the structural availability of a member by means of the failure model defined together with a structural repair model. The structural availability calculations in this study follow current theories on the operational availability of typical failure-repair systems (Kumamoto and Henley, 1996). Two examples are included at the end of this paper: one concerns a simple beam case, and the other concerns a longitudinal stiffener case based on actual ship design data. The feasibility and advantages of the method proposed can be understood well from these examples.

2. Structural availability quantification method

This paper presents a means of quantifying the structural availability of a slender beam element on which external random loads are repeatedly applied for a long period. A slender beam is considered an ordinary element of various structures. For typical beam elements affected by external loads, several failure modes, such as yielding, buckling, and fatigue, can result when loads are excessive. Of the various failure modes, the yield strength against lateral bending deflection is addressed in this paper, as it is a typical and fundamental mode considered in structural design.

A given beam element is continuously exposed to repeated random loads from the natural environment (e.g. waves and winds). When a single random load that is virtual and typically covers the probabilistic features of every load throughout a beam's design life is considered, it can be assumed that the beam element should experience the single random load one by one in sequential order at a specific frequency over its lifetime. The distribution of the single random load can be determined from a specific probability function based on the load's stochastic properties. In this study, the event that a beam experiences the single random load is defined as a Single Load Event (SLE). Accordingly, the situation that a beam element is affected by a broad range of loads over a long period can be simplified as a series of numerous individual SLEs.

Once a beam element undergoes a SLE, one of two outcomes can result in terms of yield strength: ‘success’ or ‘failure’. Here, ‘success’ occurs when the bending stress in the beam is not greater than the nominal yield stress of the material used, while ‘failure’ implies that the bending stress is greater. For this reason, it is possible to apply the Bernoulli trial assumption and the Poisson approximation to a series of numerous SLEs. The probability of beam failure for one SLE is estimated from structural reliability analysis, and the corresponding failure model is defined from the failure probability. This study simply assumes that the repair model for beams should have an exponential distribution. Ultimately, the structural availability of a beam is calculated quantitatively based on the failure and repair models. Fig. 1 depicts an outline of the structural availability method. A detailed description of the method is provided in subsequent parts of this section.

2.1. Bernoulli trial assumption

Essential assumptions on the environmental loads on a beam element are made in this study, as follows.

- Random loads: the magnitude of each load is fully random.
- Independent loads: all loads are independent of one another.
- Periodic loads: each load occurs repeatedly over a certain time interval without a break (e.g., a random load is subjected to a beam every 10 s throughout a structure's lifetime).

Based on the assumptions listed above, the situation that a slender beam element experiences large numbers of external loads for a long time is simplified as a periodic and sequential series of numerous SLEs. With respect to a slender beam and its yield strength, a random variable, Y, can have a value of one when the outcome of the SLE is a ‘success’ or zero when it is a ‘failure’. Thus, the probability of Y is given by

$$P[Y = 1] = 1 - P_f \tag{1}$$

$$P[Y = 0] = P_f. \tag{2}$$

Here, the probability of failure, P_f, for the SLE has a value from zero to one. Important features of the SLE are summarized as follows:

- one SLE is statistically independent of the others,
- one SLE is statistically identical to the others,
- an outcome from one SLE is either a ‘success’ or ‘failure’ for the yielding failure of a beam element, and
- the two outcomes from one SLE are mutually exclusive.

Consequently, the SLE becomes a Bernoulli trial, and the random variable, Y, is a Bernoulli random variable.

2.2. Poisson approximation

As noted above, the situation in which a slender beam element continuously and periodically experiences numerous random external loads throughout its lifetime, T_L, can be simplified such that an SLE occurs N times over a time period of T_L (i.e., a series of Bernoulli trials). The number of SLE occurrences over a lifetime, N, is generally considered to be sufficiently large. According to statistical theory, a series of numerous Bernoulli trials follows a binomial distribution. Let us define a random variable, X, as the number of failures occurring when SLEs occur N times over a period of T_L.

$$X \sim B(N, P_f) \tag{3}$$

The probability of k occurrences of failure or the probability when $X = k$ is as follows.

$$P(X = k) = {}_N C_k P_f^k (1 - P_f)^{N-k} = \frac{N!}{(N-k)!k!} P_f^k (1 - P_f)^{N-k} \tag{4}$$