Ocean Engineering 148 (2018) 43–52

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Reliability-based safety factor for metallic strip flexible pipe subjected to external pressure

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ARTICLE INFO

Keywords:
Metallic strip flexible pipe
Reliability analysis
Monte-Carlo simulation
FORM
Partial safety factors

ABSTRACT

Reliability-based safety factors for metallic strip flexible pipes(MSFP) subjected to external pressure are calibrated in this paper. The partial safety factors of such pipes are obtained by introducing a target reliability index and using a combination of Monte-Carlo simulation and FORM. The relationship between the safety factors and the coefficient of variation for key basic variables as well as the impact of different distribution types for both the resistance and load effect parameters on the calibrated results are investigated. Recommended design safety factor for MSFP is given similar to the widely used design safety factor for conventional metallic pipes. The calibration process presented in this paper is relatively easy to understand and to carry out. This also applies to cases with multiple components and even requiring complex iterations in relation to the mechanical model. The results obtained here can provide some guidance in connection with manufacturing procedures at the initial design stage of the MSFP.

1. Introduction

Metallic strip flexible pipes (MSFP) represent a novel category of composite pipes. Similar to classic flexible pipes, they are composed of an inner PE layer, an outer PE sheath, and helical metallic layers. The difference from other flexible pipes is that the metallic layers in MSFP are of a simple type. They do not contain the complicated interlocked carcass layer, the pressure armour layer, and the tension armor layers, which are the essential constituents in flexible pipelines (API RP 17B, 2008). Instead, the MSFP only consist of helically wound steel strips. This simplified configuration makes MSFP much more cost effective due to the convenient manufacturing process. Its typical cross section and manufacturing process are shown in Fig. 1. Compared with the widely applied reinforced thermoplastic pipes (RTP), MSFP do not only possess the good properties of RTP, but they can also contribute a lot to improve on-bottom stability properties because of their relatively heavier weight. Therefore, for shallow water applications, where the operating requirements are not so demanding, MSFP may represent a first choice of pipe concept. Although MSFP are designed primarily for shallow water applications, its collapse capacity with respect to external overpressure is still a great challenge due to the lack of a carcass layer. During operation, MSFP might face a number of uncertainties that also represent a challenge. This implies that application of design safety factors which are adequate in order to ensure a sufficient reliability level is of key importance. Hence, the reliability level of MSFP when subjected to external pressure needs to be quantified and kept at a high enough level. Appropriate design safety factors should be prescribed in order to reach this target safety level, but also in order to avoid unnecessary conservatism.

During the last decades, comprehend amount of research has been performed within the area of pipeline reliability analysis. Babu and Srivastava, 2010 addressed the reliability associated with buried flexible pipe-soil systems. Tee et al. (2013) investigated the reliability level associated with underground flexible pipes. Extensive analyses relating to reliability of pipelines with corrosion defects can also be found in the existing literature (Ahammed and Melchers, 1996; Teixeira et al., 2008; Leira et al., 2016; Larin et al., 2016). As for reliability-based safety factors to be applied for pipeline design, Boyer, et al. (1997) undertook the calibration of design safety factors for a composite pipe in order to illustrate the different steps of the procedure. Leira et al. (2005a, 2005b) proposed a structural reliability-based approach for fatigue analysis of flexible pipes and established the relationship between the fatigue safety factors and the inherent failure probability. Based on the above method, dos Santos Loureiro Filho et al., 2012 performed a calibration of safety

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https://doi.org/10.1016/j.oceaneng.2017.10.025
Received 12 May 2017; Received in revised form 26 August 2017; Accepted 16 October 2017

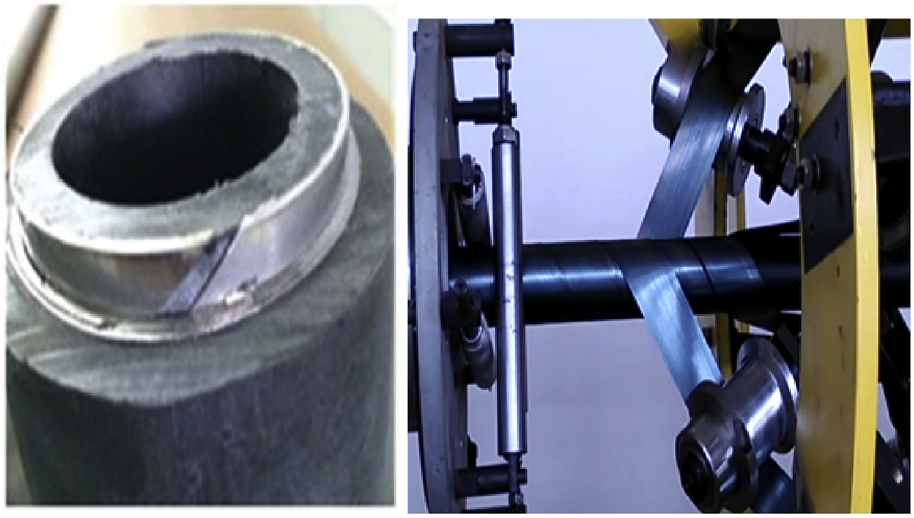

Fig. 1. Cross section and manufacturing process of MSFP.

factors to be applied for fatigue analysis of flexible riser tension armours. Avrithi and Ayyub (2010) described the development of design equations according to the load and resistance factor design (LRFD) method for loads that cause primary stress for different levels of piping operation and illustrated the partial safety factors for different values of the target reliability index. In the same year, Machida, et al. (2010) illustrated the evaluation of partial safety factors for parameters related to flaw evaluation of pipes, and proposed the important matter which should be paid attention to in the setup of the safety factors used in flaw evaluation. Fairchild et al. (2016) described the use of the previous full-scale tests data to develop a safety factor for strain-based engineering critical assessment of pipelines. Likewise, in combination with experimental data, Schillo, et al. (2017) suggested a reliability based calibration method of safety factors for the unstiffened composite cylinder shell relying on extensive measurements regarding the statistical characteristics of the geometrical and material properties of 11 previously tested composite cylinders.

As MSFP is a relatively new type of pipe concept, its mechanical behavior is still not fully understood, not to mention the inherent reliability level during operation. According to the best knowledge of the authors, there are hardly any publications dealing with calibration of safety factors for MSFP. As the collapse pressure is of primary concern for the ultimate capacity of pipelines in operation, the safety factors associated with design to withstand external pressure are calibrated in the present paper.

A simplified mathematical model for calculating the collapse pressure of MSFP can be obtained from recent work performed by Bai et al. (2016a). For the classic analytical model associated with elastic buckling of a ring or a cylinder, the calculation is straightforward. However, the plastic behavior of the PE material has a significant impact on the collapse pressure. The nonlinearity of the PE material which is taken into account in Bai's (2016a) capacity model improves the accuracy of the results, but also introduces some challenges in relation to the reliability-based safety factor analysis. The purpose of this paper is to propose a calibration process for MSFP by using a combination of Monte-Carlo simulation and FORM. The method was referenced and extended from the reliability analysis of RTP in Ref. (Bai et al., 2017). Sensitivity analyses are conducted with respect to the key parameters which influence the values of the safety factors. The design safety factor for MSFP is recommended at the end of the paper. The factor is to be seen in light of the design safety factor of 1.5 (Zhu, 1993) which is widely applied for conventional pure metallic structures(pipes).

2. Calibration process for safety factors

Uncertainties are always involved when conducting strength evaluation and structural analysis. Before starting the calibration, the basic variables corresponding to the design parameters should be determined, and the uncertainties related to the prediction of resistance and load effect should be taken into account.

As the MSFP is composed of many layers, the basic variables are too many to calculate the associated probability exactly when using full integration or general reliability methods. The accuracy and feasibility of the well-known first and second order reliability method (FORM/SORM) in estimating the results can be rather dubious in the present case. In addition, an iterative method is required in order to calculate the resistance of the MSFP. This makes it very demanding to apply FORM/SORM techniques directly. Here, the Monte-Carlo method can be regarded as a good approach in order to estimate the statistical properties of the resistance term. First, groups of random sample values of the basic variables related to the resistance of the MSFP can be generated according to their respectively stochastic models. By introducing all those generated variables and uncertainty factors into the resistance model, a corresponding array of the collapse pressure can be obtained. Through the statistical analysis, the distribution type and the corresponding parameters of the resistance term can be obtained. With the statistical models of the resistance and load random variables R and S being known, it is easy to calculate the failure probability P_f and the corresponding reliability index β:

$$P_f = prob(R < S) \tag{1}$$

$$\beta \approx \Phi^{-1}(-P_f) \tag{2}$$

where, $\Phi^{-1}(\cdot)$ is the inverse of the standard normal distribution function. As the limit state function has a simple form with statistical models established through the above simulation steps, the well-known methods mentioned above can now be used to calculated the reliability, such as FORM, SORM, Importance sampling, etc. Among these methods, FORM is particularly popular as it is easy to understand and efficient to apply. Furthermore, it can provide relatively accurate result. The reliability index in FORM is obtained by calculating the shortest distance from the origin point to the limit state surface in the standard normal space, and the corresponding point in the limit state surface is referred to as the design point. This point is also crucial in order to calculate the partial