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Li, Xiao; Jiang, Xiaoli; Hopman, Hans

DOI
10.5937/fmet1803306L

Publication date
2018

Document Version
Final published version

Published in
FME Transactions

Citation (APA)
Li, X., Jiang, X., & Hopman, H. (2018). Prediction of the critical collapse pressure of ultra-deep water flexible risers: A literature review. *FME Transactions*, *46*(3), 306-312. https://doi.org/10.5937/fmet1803306L

Prediction of the Critical Collapse Pressure of Ultra-Deep Water Flexible Risers– a Literature Review

Xiao Li
PhD Researcher
Delft University of Technology
Department of Maritime and Transport
Technology
Netherlands

Xiaoli Jiang
Assistant Professor
Delft University of Technology
Department of Maritime and Transport
Technology
Netherlands

Hans Hopman
Professor
Delft University of Technology
Department of Maritime and Transport
Technology
Netherlands

Flexible riser is a device which transports production fluids between floating vessels and subsea wells. With fewer remaining easy-to-access oil fields nowadays, flexible risers are being required to be installed in a water depth of over 3000m. However, the hydrostatic pressure at such a water depth may cause the collapse of flexible risers, and therefore predicting the critical collapse pressure is of great importance to their design. Riser collapse is a complex phenomenon related to material properties, geometry of the pipe and its overall surface topography and, therefore, makes the prediction of critical pressure challenging. Collapse prediction approaches of flexible risers have been developed for decades, yet a comprehensive review on their predictive capabilities, efficiency and drawbacks is lacking. In this paper, the recent advances on collapse studies of flexible risers are reviewed, which summarizes the methods developed for critical pressure prediction and highlights the related gaps in current research. This review aims to facilitate the current anti-collapse design and be a baseline for future utilization of flexible risers in deeper water expansion.

Keywords: *flexible riser, ultra-deep water, hydrostatic collapse, critical pressure.*

1. INTRODUCTION

With the gradual depletion of easily exploitable gas and oil fields, the oil and gas industry has moved into deeper offshore areas to find growth [1], [2]. As one primary riser device for deepwater drilling and floating production, flexible riser, is being required to extend its current limits to meet that increased ultra-deep productions [3].

Flexible riser is a pipelike structure which consists of multiple layers of wound metal bands and extruded polymers. A typical internal configuration of flexile riser is shown in Figure 1 [4]. Along the axial direction from inside to outside, those layer are [5]

- Interlocked carcass: the innermost layer made from duplex steel. It is designed to resist external pressure loads.
- Inner liner: an extruded polymeric layer providing internal fluid integrity.
- Pressure armour: an interlocked structure that provide resistance to internal pressure.
- Tensile armour: the outmost metallic layer, which supplies axial rigidity and burst resistance.
- Outer sheath: an extruded polymeric layer that acts as the external fluid barrier.

Owing to the advantages of flexibility and reduced installation cost and time, flexible riser system has been applied to oil & gas production in shallow water over four decades with an established technology [6]. However, cost and technical challenges of the flexible riser system increase significantly with water depth, requiring the current technology envelopes of flexible risers to be extended for the deep/ ultra-deep water exploration [3].

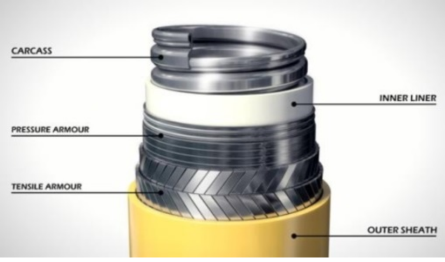

Figure 1. Typical design of a flexible riser (insulation and anti-wear layers are not shown)[4]

Flexible riser may occur radial buckling due to the increasing external pressure with water depth. This buckling failure is referred to as collapse (Figure 2) and the minimum collapse pressure is called "critical pressure" [7]. The collapse failure is commonly divided into two types, dry and wet collapse, depending on the annulus conditions of risers [8]. Dry collapse may occur when the outer sheath is intact and all layers within the riser play a role together to resist the external hydrostatic pressure. In this scenario, the interlocked carcass and the pressure armor are the most important layers in dry collapse resistance, as they contribute the most to radial stiffness. If the outer sheath is breached,

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Received: January 2018, Accepted: March 2018
Correspondence to: Xiao Li, PhD researcher, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, the Netherlands
E-mail: X.Li-9@tudelft.nl
doi:10.5937/fmet1803306L

the seawater floods the annulus and then the external pressure acts directly on the inner liner. This situation, named wet collapse, represents the most extreme loading conditions, since the whole external loading is resisted by the carcass alone. Flexible riser is particularly vulnerable at the touchdown point (see Figure 3) during the installation, when there is no balancing pressure in the internal bore and the collapse resistance is further reduced due to the bending loads [9]. To prevent such kind of incidents, the flexible risers applied to deep/ ultra-deep water production, is thus required adequate anti-collapse capability. This capability often becomes a govern factor of pipe wall thickness and production cost [10], [11]. Therefore, the understanding of collapse failure and related riser performance characteristics is important for give a reliable prediction of critical pressure and guide the anti-collapse design of flexible riser systems [12].

Figure 2. Collapse failure of the flexible riser [7]

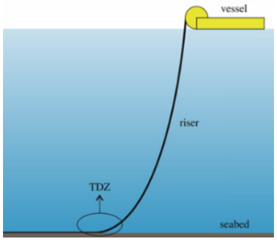

Figure 3. Touchdown zone during installation [13]

At present, there is no available comprehensive overview towards the critical pressure prediction of flexible risers under sea environments. This paper is intended to clarify the estimation methods of critical pressure and highlight the current research gaps, which is organized as follows. In Section 2 the common approaches for critical pressure estimation are reviewed. Section 3 lists the current research gaps within the prediction approaches and the final section concludes the work.

2. PREDICTION APPROACHES OF CRITICAL PRESSURE

Various standards have been developed with respect to the design of risers. Among them, API 17B and 17J are two widely acceptable specifications for flexible pipes issued by American Petroleum Institute [8], [14]. For a flexible pipe that applied to deep-water production, however, these specifications are not able to provide an available approach to calculate the critical pressure of the carcass (the main component for the collapse resistance). In their latest versions (2014), no prescriptive methodology except only a safety factor was given to guide the anti-collapse design of the interlocked carcass. That reveals that standardized methods have not been established yet for anti-collapse design of flexible risers and therefore, how to predict the critical pressure is still a gray area for riser designers.

Determining the critical pressure through the collapse tests (Figure 4) of flexible risers is always the most reliable way for the anti-collapse analyses [10], [15], [16]. However, such hydrostatic tests require specialized hyperbaric chambers, which are very limited worldwide [17]. In additional, those costly tests are unable to be an effective approach to evaluate parameter variations readily for structural optimization design.

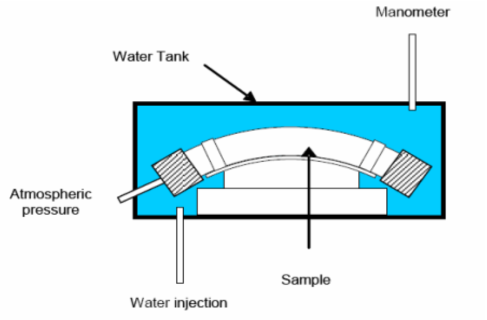

Figure 4. Test set-up for curved collapse test [10]

In that regard, analytical and numerical approaches are developed to give a prediction of the critical pressure of the carcass. For the most part, the analytical approaches has been limited to highly simplified analytical models due to the complexity of the carcass profile, aided by experimental calibration [18]. The most difficult step in that simplification of flexible risers is how to address the complex carcass profile, which is in an interlocked shape (Figure 5 [19]). Since the carcass presents a similar stability behavior to a ring or tube, a method refers to equivalent layer method is proposed to transform the carcass into an equivalent ring or tube. Such kind of equivalent methods will be elaborated in the following section. This method enables the treatment of the carcass as a solid ring so that the elastic ring buckling theories can be used to solve the critical pressure [20], [21]. Some analytical models [22], [23] developed based on that ring buckling theories were recommended by ISO 13628-11 [24]. However, these analytical models are developed for the carcass alone, which are unable to consider the supporting pressure armor and geometric gaps.

Figure 5. Geometric profile of interlocked carcass [19]

By contrast, the FE techniques allow to consider more layers than only a carcass in the collapse analyses. Although numerical analyses can be performed by modelling the flexible risers with all the metallic and polymeric layers, such analyses are computational intensive because of tremendous finite elements of the models. Moreover, the solutions may become unstable due to the stiffness matrix becoming singular [25]. Considering that, simplified flexible riser model has been adopted by researchers. Tensile armour and non-metallic layers are excluded in the numerical simulation since they contribute little to collapse resistance. Such numerical simulations are often divided into two types: 3D full FE models and simplified FE models (2D or 3D). The 3D full model refers to modelling the interlocked layers, carcass and pressure armour, with their actual rolled shapes. Such kind of FE models were constructed by Neto et al. [18], [26] and could be used to investigate stress concentrations for their preservation of layer geometric details. However, the full FE models are still impractical for design purpose of flexible risers due to the onerous modelling producedure and time-consuming computation. Therefore, simpler numerical models are developed as an alternative of full FE models with the equivalent layer methods described above.

Current simplified numerical models include 2D FE models and 3D simplified FE models. The interlocked layers in these models are treated as an equivalent ring (2D) or tube (3D). These simplified models are often employed to conduct sensitivity analysis of collapse resistance on geometric imperfections (initial ovalization and gaps) [27] as well as the post-buckling mode inves–tigation of carcass [28], [29]. Although the simplified models simplify the modelling procedure and reduce the computational time, they may lead to incorrect predictions of stress concentrations due to the loss of geometric profile details [26].

3. CURRENT RESEARCH GAPS

Following the prediction approaches illustrated in Section 2, research gaps within the literature can be classified into three main categories: (1) equivalent layer methods; (2) flexible riser imperfections and (3) pipe curvature. The following sections elaborate on the methods used in each category.

3.1 Equivalent layer methods

The main difficulty in predicting the critical pressure of flexible risers with either numerical or analytical approach is always the necessity to address complex profiles of interlocked layers. To overcome this difficulty, equivalent layer methods are developed to treat the helical wire as a homogenous ring that displays the same collapse behavior as the carcass. For the models intended for anti-collapse design, a reliable equivalent layer method is the basis of accurate prediction of critical pressure. The main purpose of most proposed methods is to determine the thickness of the equivalent layer.

Up to now, several equivalent layer methods have been proposed to calculate the thickness t_{eq} for that equivalent homogenous layer. Those methods are proposed by imposing geometric or mechanical equity between the interlocked carcass and the equivalent ring, such as the cross sectional area [30], the bending stiffness [31], [32] or the strain energy [33].

Area equivalent method is carried out based on the equivalence of cross-sectional areas [30], which is given as:

$$t_{eq} = \frac{nA_x}{L_p} \tag{1}$$

where n is the number of carcass strips, A_x is the strip cross-sectional area, L_p is the pitch of carcass. As the cross-sectional area is the only parameter considered in this method, the actual material distribution in the carcass profile is not accounted and hence the accuracy of the prediction may not be guaranteed.

Since the radial buckling of ring-like structures is a bending-dominated problem [20], Martins et al. [32] constructed the ring model by equating the bending stiffness per length of carcass and the equivalent ring. The equation takes the form:

$$t_{eq,3} = \sqrt[3]{\frac{12I_{G\min}}{L}} \tag{2}$$

Where $I_{G\min}$ is the minimum moment of inertia of the carcass cross section, L is the length of the carcass.

A similar method was carried out by Loureiro et al. [34], who developed a homogenous ring model that possesses an equivalent bending stiffness per area of the interlocked carcass layer:

$$t_{eq} = \sqrt{\frac{12I_{G\min}}{A}} \tag{3}$$

Where A is the cross-sectional area of the carcass. This method is originated from Cruz and Dias [31], who treated the carcass as an anisotropic shell on the basis of the theory of plates and shells [35].

Considering that most equivalent methods were unable to consider the material elastic-plasticity, Tang et al. [33] proposed a method bases on the structural strain energy equivalence, which is given as:

$$t_{eq} = \frac{\psi_{carcass}}{\frac{\pi}{4} A_1 \varepsilon_\theta^2 RL} \tag{4}$$

where ψ_{carcass} is the strain energy of the carcass, R is the radius, ε_θ is the hoop strain, A_1 is a parameter that takes the form:

$$A_1 = E\frac{1-v}{(1+v)(1-2v)} \tag{5}$$

where E is the elastic modulus and v is the Poisson's ratio.

However, this method always requires a carcass FE model to calculate its strain energy and the boundary conditions applied to this model conditions enhance the structural stiffness of the carcass, lowering its absorbed strain energy. As a result, the thickness of the equivalent layer is underestimated.

Table 1. Summary of existing equivalent layer methods

Equivalent layer method	Section geometry	Material factors		FE required
		Linear elasticity	Elastic-plasticity	
Bending stiffness per unit area	✓	✓	×	×
Bending stiffness per unit length	✓	✓	×	×
Area equivalence	✓	×	×	×
Strain energy equivalence	✓	✓	✓	✓

Table 1 summarizes the common equivalent layer methods and gives an overview towards their own characteristics. To gain an insight of the reliability of the existing equivalent layer methods, Lloyd's Register Energy [36] conducted an investigation on the prediction accuracy of the mathematic models with different equivalent layer methods. The results shown a considerable variation existed in the predictions between different equivalent methods, indicating that further development of these methods is needed.

3.2 Flexible pipe imperfections

The collapse resistance of a flexible riser is affected by the following pipe imperfections. Determining their effects on critical pressure is important for the anti-collapse design of flexible risers.

- Geometric imperfections
- Material anisotropy (induced by cold work)
- Residual stress

Practical pipe structures are manufactured to specified tolerances, and as a result the interlocked layers always exhibit some degree of ovality. In addition, the volume of polymeric layers changes due to material degradation and factory acceptance test (FAT), which creates unclosed gap between layers [27], [37]. These geometric imperfections may trigger a premature radial stiffness reduction to the interlocked carcass, which had been evidenced in the sensitivity analyses conducted in [27] and [29]. The interaction of ovalization and gap makes the collapse failure mechanism of carcass complicated. The current proposed analytical models could only consider the pipe ovalization [22] and thus these imperfection are often studied numerically. However, the numerical analyses cannot be an effective approach for the preliminary design, which are unable to quantify the effects of geometric imperfections. Each change has to be revaluated through model reconstruction, leading to a cumbersome design procedure. Therefore, an analytical model is demanded to allow examination of imperfection variations, helping reach the maximize anti-collapse performance of flexible risers.

Due to the cold work during the carcass manufacturing process, strain hardening may occur, causing a high degree of stress-induced material anisotropy[38], as shown in Figure 6. This cold work makes the material properties varied throughout the formed profile of the carcass strip, complicating the collapse behavior of carcass along with the structural anisotropy. However, the exact amount of the cold work is hard to measure directly, posing barriers in defining the material stress-strain curves for the cold formed sections. To address this problem, approaches are carried out to determine the material stress-strain curves for the cold formed sections or entire cross section of carcass strips. Axelsson [27] obtained the stress-strain curves of the carcass curved section depends on their yield strength, which was estimated through hardness measurements. Nogueria [39] and Lacerda [40] defined an average bilinear stress-strain curve for the entire carcass profile. The parameters of this curve needed to be calibrated by carcass load-displacement tests. Although those studies provided some potential ways to estimate the cold work level, further investigations are needed to determine its exact amount.

Figure 6. Manufacture process of carcass layer [41]

Residual stress is an imperfection also generated from the manufacturing process. Owing to the practical difficulties, the residual stresses contained in the carcass strip cannot be relieved after it has been wrapped onto a bobbin [42]. As the interlocked layers are embedded within tensile armors, it is extremely difficult to measure the residual stress of interlocked wires in-situ. Conventional destructive methods such as hole-drilling are no longer applicable. Therefore, some non–destructive methods, e.g. X-ray diffraction [42] or neutron diffraction methods [43], are employed by researchers to establish the preliminary studies of residual stress measurement.

3.3 Pipe Curvature

During deep/ ultra-deep water installation and operation, flexible risers experience bending within the touchdown zone (TDZ). The bending configuration may change the ovality and gap of the pipe curved regions, leading to a reduced collapse resistance [15]. The complexity of curvature effect poses barriers to analytical approach and limits most curved collapse studies to finite element methods. A simplified 3D solid model comprised carcass, inner liner and pressure armor was carried out by Lu et al. [44] to study the curved collapse. Interlocked layers in this model were modelled as helical strips (like a spring ring). The prediction accuracy of this model was later examined in [15], which indicated that the predictive model provided the flexible pipe products a more than adequate anti-collapse capacity compared with the anticipated design values. Since that simplified model did not offer the engineers a physically intuitive observation and trustworthy prediction on the curvature effect, a 3D full FE model was constructed by Neto et al. [45] to visualize the curvature effects in the flexible pipes. They found it caused a radial stiffness change in the pipe curved regions and imposed different impacts on dry and wet collapse. For dry collapse, the reduction induced by curvature on collapse resistance was negligible while in wet collapse, the decreasing effect was significant. However, the construction and computation of such a 3D full model are time-consuming, suggesting the further development of simpler models, based on test data, is required.

4. CONCLUSIONS

As oil and gas exploitation moved towards ever deeper water fields, more technical challenges related to anti-collapse capabilities of flexible riser occur. The main challenges include:

1) Complexity of the interlocked layer profiles

Carcass and pressure armour are manufactured with helicoidal interlocked strips, which make their mechanical behaviors complex when subjected to external pressure. This also brings troubles to the numerical analyses, making them time-consuming.

2) Reliablity of existing equivalent layer methods

Up till now, various equivalent methods are developed to treat the interlocked layer as a solid ring. However, most of them are proposed by imposing equity between the carcass and homogenous ring for one certain property and the layer thickness has always been the only output for the equivalent layer. Moreover, all of them fail to capture the actual structural stiffness of interlocked layer due to the neglect of contact issues. As a result, their predictions of the critical pressure of the carcass often result in considerable errors.

3) Imperfections and pipe curvature

Most studies with respect to pipe imperfections were carried out over geometric imperfections while the investigation on other kinds of imperfection are quite limited. How to measure and quantify the cold work level of carcass strip and the residual stress contained by the interlocked layers may have impacts on the accuracy of prediction methods. For pipe curvature, it influences other factors like layer ovalization and gap width, making the curved analyses an onerous tasks. To gain an insight of this effect, further investigations are required.

Ultra-deep water collapse study of flexible risers is a complicated task but of great importance to the oil and gas industry. For the increasingly harsh conditions that are hard to test for, an accurate and reliable collapse prediction technique would provide a well-determined operation limit for the flexible riser product, helping save costs and increase riser operators' confidence. For the future trends of flexible riser, such a technique will also be a powerful tool to be compatible with the composite material and new riser system technologies.

ACKNOWLEDGMENT

This work was supported by the China Scholarship Council [grant number 201606950011].

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ПРЕДИКЦИЈА КРИТИЧНОГ ПРИТИСКА КОЛАПСА КОД ФЛЕКСИБИЛНИХ ЗАТЕЗАЧА

ПОСТАВЉЕНИХ НА ВЕЛИКОЈ МОРСКОЈ ДУБИНИ – ПРЕГЛЕД ЛИТЕРАТУРЕ

К. Ли, К. Јианг, Х. Хопман

Флесксибилни затезач је уређај који врши транспорт радних флуида између плутајућих пловила и подземних бунара. Све мањи број лако доступних нафтних поља намеће потребу инсталирања флексибилних затезача на дубини мора већој од 3000 м. Међутим, хидростатички притисак на таквој дубини може да изазове колапс флексибилних затезача, па је стога предикција критичног притиска колапса од великог значаја при њиховом пројектовању. Колапс затезача је сложени феномен повезан са својствима материјала, геометријом цеви и топографијом укупне површине и зато предикција критичног притиска представља велики изазов. Деценијама се развијају различити приступи предикцији колапса флексибилних затезача, међутим недостаје свеобухватан приказ могућности, ефикасности и недостатака предикције. Рад приказује најновија истраживања колапса флексибилних затезача, сумира методе за предикцију критичног притиска и указује на пропусте актуелних истраживања. Циљ рада је да олакша пројектовање антиколапс затезача и да буде основа за будућу ширу примену флексибилних затезача у водама веће дубине.