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ABSTRACT

Flexible risers that for deep-water production are designed with strong collapse capacity. However, this collapse capacity is susceptible to pipe curvature in the flooded annulus condition. For the curved riser sections within the touchdown zone, significant reduction of collapse capacity can occur once the external sheaths are worn out, resulting in the so-called 'wet collapse'. Therefore, the collapse capacity of flexible risers should be well-determined during design stage. Mostly, curved collapse analyses are performed through costly numerical simulations since there is no well-established analytical models . This study focuses on the wet collapse mechanism of curved flexible risers, aiming to pave the way for the development of analytical solutions. 3D full FE models were adopted to gain insight into the wet collapse mechanism of curved risers, which had been verified by the data from public literature. The investigation indicates that the deformed cross-sectional shape of the carcass is the dominant factor of the curvature effect.

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KEYWORDS
Flexible pipes; curvature effect; wet collapse behaviours; FEA

1. Introduction

Over the past 40 years, the water depth of the subsea fields for oil and gas production has increased from 125 m (1977, Roncador field) to 2900 m (2016, Stones field) (Silva and Damiens 2016; Moore et al. 2017). As the key device for transporting hydrocarbon product from sub-sea reservoirs to floating vessels, flexible risers therefore have to withstand huge hydrostatic pressure without collapse. Flexible riser are multilayered tubular structures which consist of helical wound metallic strips and tapes, and extruded polymeric layers (Rahmati et al. 2016), as shown in Figure 1 (National Oilwell Varco 2014). The carcass and the pressure armour are two self-interlocking layers wound by metal strips with constant pitches, which take external and internal pressure, separately. The polymeric inner liner in-between is a leak-proof barrier to contain fluids in the pipe bore. Tensile armours form in pairs to provide tension, bending and torsional resistances. The outer sheath is the water barrier for the seawater outside.

Normally, the external pressure is resisted by all the layers of flexible risers together if the outer sheath keeps intact. Collapse failure of the flexible riser with intact outer sheath is referred as 'dry collapse' (Gay Neto et al. 2016). Once the outer sheath is breached in the ocean environment, sea water then floods the riser annulus and acts directly on the inner liner, as illustrated in Figure 2 (Crome 2013; Mahé 2015). This situation represents a severe loading condition since most of the external pressure is carried by the carcass. Other layers, mainly the pressure armour, contribute to the collapse resistance of the carcass by restraining its radial deformation only. In this flooded situation, the buckling failure caused by hydro-static pressure is referred as 'wet collapse' (Gay Neto et al. 2017).

At present, the collapse capacity of a flexible riser is designed based on this 'wet collapse' concept. For a given water depth, the hydro-static collapse design of a flexible riser needs to be confirmed by a wet collapse calculation. Owing to the structural flexibility, flexible risers are curved naturally in the touchdown zone (TDZ) or buoyed regions, as sketched in Figure 3 (Anderson and O'Connor 2012). The influence of pipe curvature on the collapse strength is negligible if the outer sheaths of flexible risers remain intact (Gay Neto et al. 2016). Once the outer sheaths are breached, however, the collapse strength of the curved flexible risers can be largely reduced. The curved collapse tests done by companies such as TechnipFMC (Technip) (Paumier et al. 2009) and BHGE (Wellstream) (Lu et al. 2008; Clevelario et al. 2010) showed that the wet collapse pressure could be reduced around 10–20 % when the pipe samples were bent to their minimum bending radius (MBR), indicating that wet collapse pressure of flexible risers is susceptible to the pipe curvature.

Although this curvature effect has been evidenced, the estimation of wet collapse pressure for a curved flexible risers remains challenges. Finite element method (FEM) stands as a powerful tool in collapse analyses. However, modelling the flexible risers is not an easy task due to the complex self-interlocking profiles of metallic layers. Furthermore, FE models in curved collapse analyses are required to be constructed adequately long in order to introduce the pipe curvature and eliminate the end effects (Gay Neto et al. 2012; Axelsson and Skjerve 2014). As a result, those 3D 'full' FE models built

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Figure 1. Typical configuration of a flexible riser (National Oilwell Varco 2014). (This figure is available in colour online.)

with detailed layer profiles are always cumbersome and time-consuming.

To reduce the computational cost, simplified FE models were developed as an alternative strategy (Li et al. 2018). One common simplification is to replace the self-interlocking layers with equivalent tubes. Such kind of simplification can be found in the work of Lu et al. (2008), which simplified the metallic layers to helical spring-like tubes that made of strips with equivalent rectangular cross section. Another simplification is to reduce the model length using a representative volume element (RVE) model with periodic conditions. This method was adopted in the work of Gay Neto et al. (2016) and Gay Neto et al. (2017), which presented a two-pitch model to simulate the 'infinitely long' flexible pipe. With the aid of displacement couplings and kinematic constrains at the cutting regions (connected to the rest of the flexible pipe), the curved pipe could be represented by this two-pitch model. Those simplified FE models require less computational cost, but their quality highly depends on the adopted equivalent layer methods and the periodic conditions.

Comparing to finite element methods, analytical approaches are much more cost-efficient. However, there is a lack of analytical models for predicting the wet collapse pressure of curved flexible risers in public literature. The main difficulty of developing such an analytical model is to determine the dominant factors for triggering the reduction of curved collapse resistance. Two possible factors were pointed out by researchers to explain the curvature effect. One is the curvature-induced pitch elongation of the carcass, which reduces the radial stiffness of its extrados, i.e. the section of the pipe which is undergoing tension during the bending process (the opposite section is called intrados) (Gay Neto et al. 2012). Another is the squeeze effect from the flattened region of the curved inner liner (von Kármán fattening effect von Kármán 1911), which imposes an additional ovalization onto the cross section of the carcass (Loureiro and Pasqualino 2012). Due to the structural complexity of flexible risers, the way in which the pipe curvature affects the wet collapse strength is still not fully understood (Clevelario et al. 2010; Loureiro and Pasqualino 2012; Edmans 2014). This poses difficulties to the development of analytical approaches.

As the production is moving towards ultra-deep water fields, the design of new riser product is being required to achieve a balance between collapse resistance and self-weight. Therefore, there is a demand to develop an efficient tool to facilitate the collapse design. In view of this, three dimensional finite element models were presented in this paper to gain insights into collapse mechanisms of curved flexible risers. The finite element studies were established to reveal the

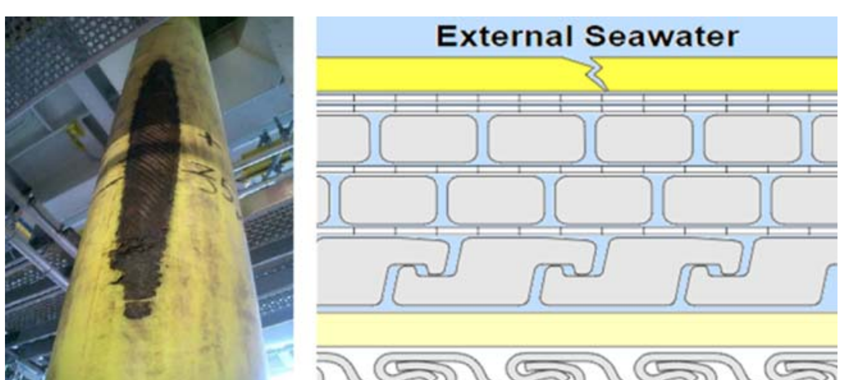

Figure 2. Flooded annulus scenario for the flexible riser with a breached outer sheath (Crome 2013; Mahé 2015). (This figure is available in colour online.)

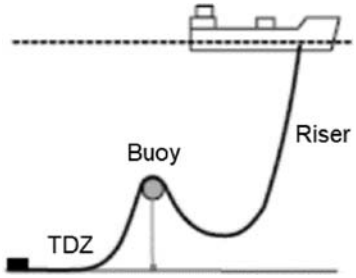

Figure 3. Flexible riser in a curved configuration (Anderson and O'Connor 2012). (This figure is available in colour online.)

dominant factors of curvature effect, paving the way for the development of analytical approaches in collapse analyses.

This paper is organised as follows: Section 2 gives a description of the 3D full FE models adopted in this study. In Section 3, case studies were carried out to investigate the effect of pipe curvature on the wet collapse behaviours of flexible risers. The results of case studies were analysed in Section 4 to identify the dominant factors in this curvature effect. Section 5 concludes the whole work.

2. Finite element modelling

To investigate the wet collapse mechanism of curved flexible risers, a 3D full FE model of 4″ internal diameter (ID) was constructed using the commercial finite element software Abaqus 6.14 (ABAQUS 6.14 2014). This FE model was developed from the prototype presented by Gay Neto et al. (Gay Neto and Martins 2012, 2014). In this section, the development of this 3D full FE model is introduced with three subsections. A model description is presented first, followed by the pipe length study in the second subsection, which aims to determine the length of the 3D full FE model for eliminating the pipe end effects. The last subsection gives the verification for the 3D full FE model with the determined length.

2.1. Model description

The FE model illustrated in Figure 4 for investigating the curved collapse mechanism was developed from a prototype given by Gay Neto and Martins (2012) and Gay Neto and Martins (2014), which consists of three layers, the innermost carcass, the inner liner and the pressure armour. In what follows, this three-layered 3D full FE model is referred as 'Model-A '. The prototype of Model-A, as shown in Figure 5, was a one quarter model of flexible pipe section that developed in ANSYS 12.0 (ANSYS 2011), which had a length of two carcass pitches. The initial ovalization imposed on the carcass in the prototype is 0.5% (Gay Neto and Martins 2014), which is defined as (API 2014a)

$$\Delta = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \tag{1}$$

where $D_{\max}$ and $D_{\min}$ are maximum and minimum pipe diameter, respectively. The same ovalization was also imposed onto the reproduced models in the followings. Table 1 lists the basic geometric and material data of the layers within the prototype. The schematic diagrams of interlocking layer profiles are shown in Figure 6, and the corresponding profile data are listed in Table 2 (Gay Neto and Martins 2012, 2014; Mendonça 2016). Detailed material constitution curve of each layer are given in the source references mentioned above.

Layer contact occurs during the loading process as the flexible riser is a multi-layered pipe structure. This was addressed by using a surface-based penalty method. According to the work of Gay Neto and Martins (2014) and Caleyron et al. (2014), a Coulomb friction coefficient of 0.15 was adopted for the tangent sliding between layers while a penalty stiffness factor of 0.1 was used in normal contact. By using the sweep meshing technique, Model-A was meshed as Figure 7. An 8-node linear brick element, C3D8R, was employed as the main element type in the meshing process of all the layers. A small amount of C3D6 elements were adopted to mesh the irregular corners of the pressure armour, which were the 6-node wedge elements (ABAQUS 6.14 2014).

Loads and boundary conditions were applied to Model-A as follows. This FE model was first bent to a specified curvature. The external pressure was then applied to the outer surface of the liner to compress the carcass into collapse. The tips of the model were constrained as two rigid regions to simulate the clamped ends. This was done by creating two reference points (RP) on the model centre line to constrain the tip nodes with multi-point constraints (MPC). These two RPs were fully fixed in the collapse analysis of straight models. In the curved collapse studies, one RP was allowed to move within YZ plane only in order to introduce the specified curvature (by applying a corresponding bending moment M_b), as shown in Figure 8. This RP was fully fixed after bending while the other RP was always fully fixed.

To maintain the specified curvature in the collapse process, two lines from the outer surface of the liner, lying on the neutral plane, were also fixed after bending, as illustrated in Figure 9. The nodes on these two lines were only allowed to move along X-axis direction within the neutral plane. This is due to the fact that the external pressure applied onto a curved pipe always restores it to a straight configuration (Gay Neto et al. 2012), as shown in Figure 10. Therefore, such a line-fixed boundary condition was defined, which is referred as 'BC1' in the following. The Riks method (Riks 1979) was adopted in the collapse analysis to capture the collapse pressure.

2.2. Length determination

To achieve the balance between computational cost and accuracy, a suitable pipe length should be determined in the numerical simulation to eliminate the end effects. In this respect, a set of sample models with the same layers were built, in which their lengths were extended from 10 to 40 carcass pitches (the pitches at two ends for clamped boundary conditions were not included), as shown in Figure 11. Those sample models were kept in straight configuration for collapse analyses, where the two RPs at their ends were fully fixed.

The wet collapse pressures of those sample models were plotted in Figure 12, which were used to identify a suitable

Figure 4. Model-A for investigating the wet collapse mechanism of curved flexible risers. (This figure is available in colour online.)

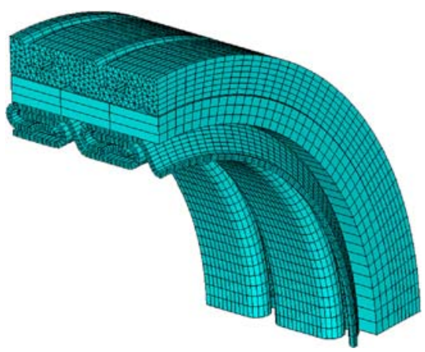

Figure 5. Prototype presented by Gay Neto and Martins (2014). (This figure is available in colour online.)

Table 1. Geometric and material properties (Gay Neto and Martins 2014, 2012).

Model	Carcass	Liner	Pressure armour
Layer material	Duplex	PA11	Carbon steel
Internal diameter (mm)	101.6	114.4	124.4
Layer thickness (mm)	6.4	5.0	7.0
Young's Modulus (GPa)	200	–	207
Poisson's Ratio	0.3	0.45	0.3
Tangent Modulus (GPa)	2.02	–	50.00
Yield stress (MPa)	600	–	650

pipe length for eliminating the end effects in numerical simulation. It can be seen that the wet collapse pressure becomes stable when the sample length was increased to 30 carcass pitches. This indicates that the end effects were almost

Table 2. Profile properties of the carcass and the pressure armour (Gay Neto and Martins 2012, 2014; Mendonça 2016).

Carcass			
Pitch length L_c (mm)	16	L_7(mm)	2
Strip thickness t_s (mm)	1	R_{tip} (mm)	0.5
L_1 (mm)	8	θ_1 (deg)	60
L_2 (mm)	3	θ_2 (deg)	45
L_3 (mm)	9	θ_3 (deg)	90
L_4 (mm)	4.5	R_1 (mm)	1
L_5 (mm)	10	R_2 (mm)	1
L_6 (mm)	3	R_3 (mm)	3
Pressure armour			
Pitch length L_{pa} (mm)	16	h_1 (mm)	2.5
b_1 (mm)	2.87	h_2 (mm)	4.5
b_2 (mm)	2.3	h_3 (mm)	7.0
b_3 (mm)	5.2	a_1 (deg)	99
r_1 (mm)	1.0	a_2 (deg)	100
r_2 (mm)	0.3		

eliminated for the sample model with a length of 30 carcass pitches. Therefore, this length was used for all the 3D full FE models presented in this work.

2.3. Model verification

Based on the pipe length studies conducted in Section 2, Model-A was constructed into 30 carcass pitches' long. To ensure the reliability of Model-A in the wet collapse studies of curved risers, a verification process, as illustrated in Figure 13, was carried out. First, the prototype was reproduced using Abaqus 6.14. After the reproduced

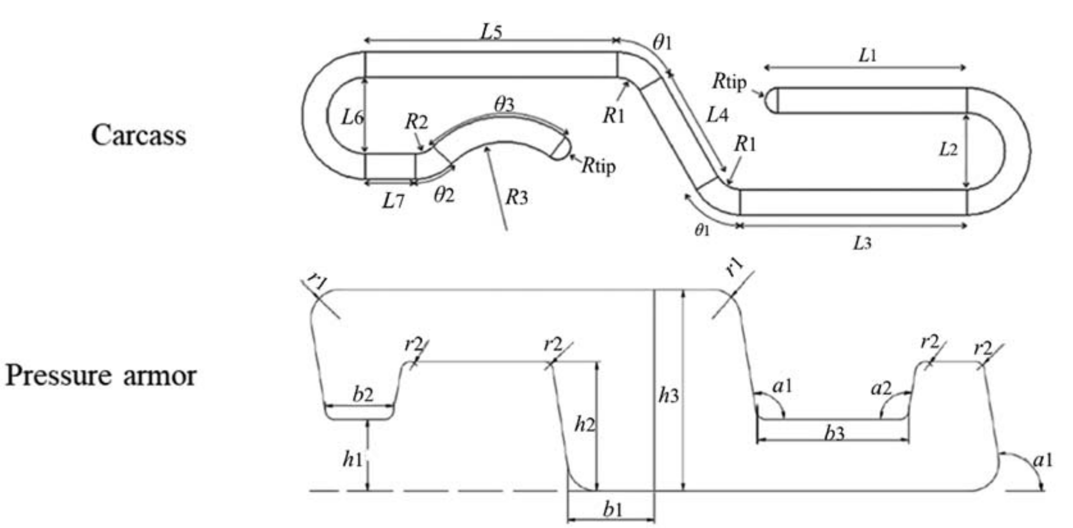

Figure 6. Schematic diagram of profiles of the carcass (top) and the pressure armour (bottom) (Gay Neto and Martins 2012, 2014; Mendonça 2016). (This figure is available in colour online.)

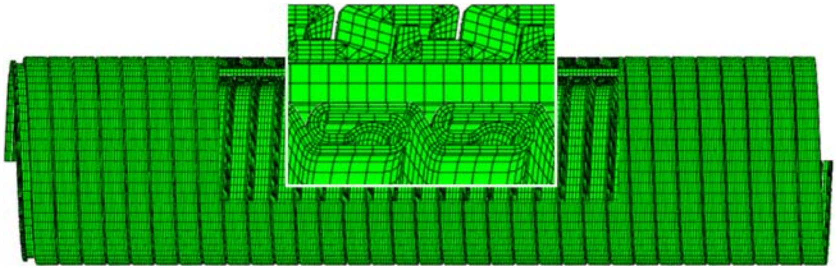

Figure 7. Mesh of Model-A. (This figure is available in colour online.)

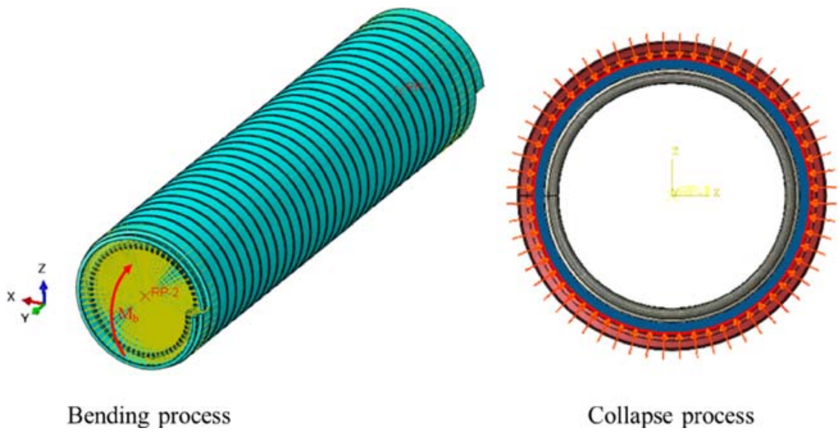

Figure 8. Constraints at the ends (left) and the applied external pressure (right). (This figure is available in colour online.)

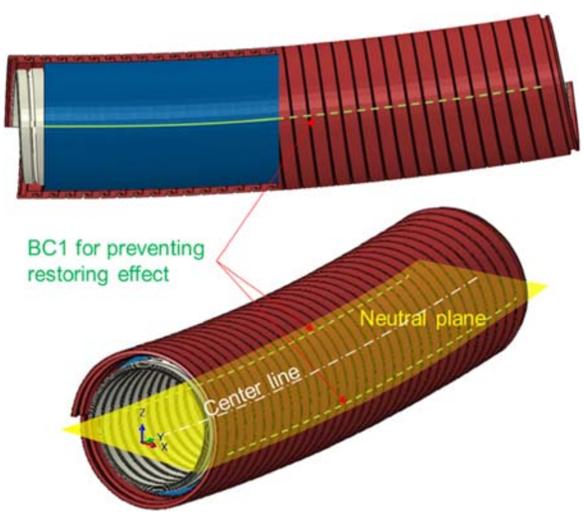

Figure 9. BC1 – fixed lines on the outer surface of the inner liner for preventing restoring effect in Model-A. (This figure is available in colour online.)

model was verified by the prototype, it was then extended to 30 pitches' long with full pipe section. If there was not much difference among the collapse pressures given by these three FE models, then the reliability of Model-A was verified.

Table 3 lists the wet collapse pressure predicted by the above-mentioned three FE models for a straight riser. The collapse pressure given by reproduced model agrees well with that of the prototype, which performs a difference less than 4%. It indicates that the prototype model was well reproduced in Abaqus. Model-A extended from the reproduced model also shows a good agreement with the prototype and the reproduced model in respect of the collapse pressure prediction. Therefore, this Model-A could be used for the following investigation.

3. Case study

Case studies were carried out to investigate the wet collapse behaviours of curved flexible risers. This section presents a detailed description of how those case studies were conducted, and what results were obtained from this investigation.

3.1. Study of curvature effect

In API 17J (2014) (API 2014b), the design criteria of MBR is defined from the concepts of minimum storage radius

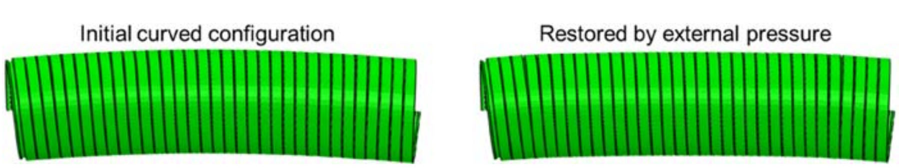

Figure 10. Curved riser (three layers) restored by external pressure to a straight configuration. (This figure is available in colour online.)

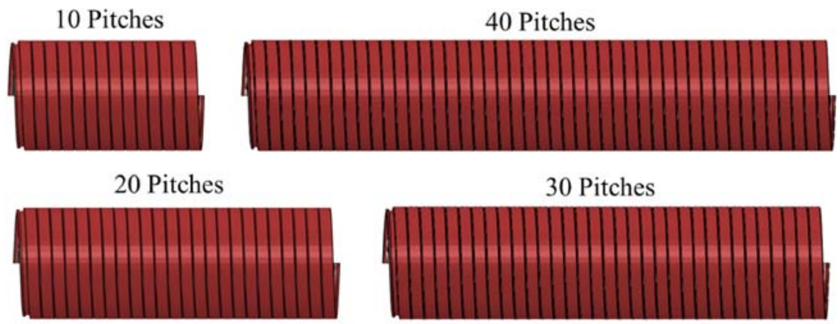

Figure 11. Sample models built in different length. (This figure is available in colour online.)

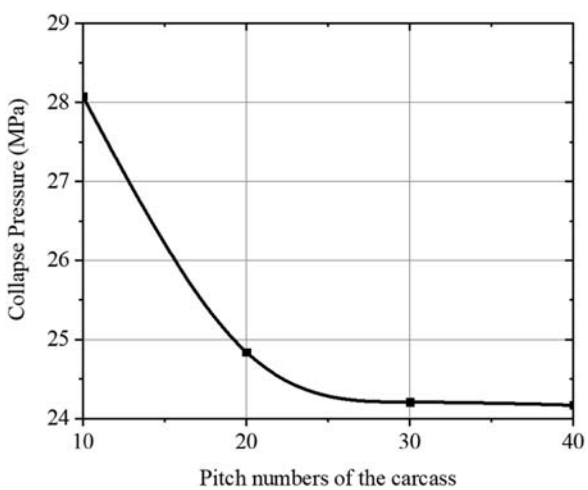

Figure 12. Collapse pressure vs. Number of carcass pitches from the sample models. (This figure is available in colour online.)

Table 3. Verification of Model-A.

Model	Pitch number	Collapse pressure (MPa)	Diff (%)
Prototype (Gay Neto and Martins 2014)	2	25.36	–
Reproduced model	2	24.36	3.94
Model-A	30	24.21	4.53

(MBR), which is at least 1.1 times the bending radius limit neither causes layer locking nor excessive strain of polymeric layers. For dynamic flexible risers, a minimum factor of 1.5 should be considered based on the MBR.

With the given layer geometry, the bending radius limits of interlocked and polymeric layers were calculated (Sævik and Ye 2016). Based on those radius limits and the design criteria, the MBR of the riser models presented in this work was determined, which was 3 m. Therefore, the minimum radius of curvature in case studies was set to 3 m. By applying bending moments to the RP at one end of Model-A, a set of radius of curvature was imposed, which were 7, 5 and 3 m. The bending moments for each specified radius of curvature were determined by a bending response study prior to this curved collapse investigation.

The curves of external pressure vs. pipe ovality given by Model-A for curved and straight risers are plotted as Figure 14. According to the results plotted in Figure 14, it seems that the curvature has little influence on the wet collapse behaviour of the curved riser. However, we noted that the cross-sectional shape from the collapse region of the carcass at the collapse moment, as shown in Figure 15, still remained an approximate bi-symmetric shape even for the pipe was bent

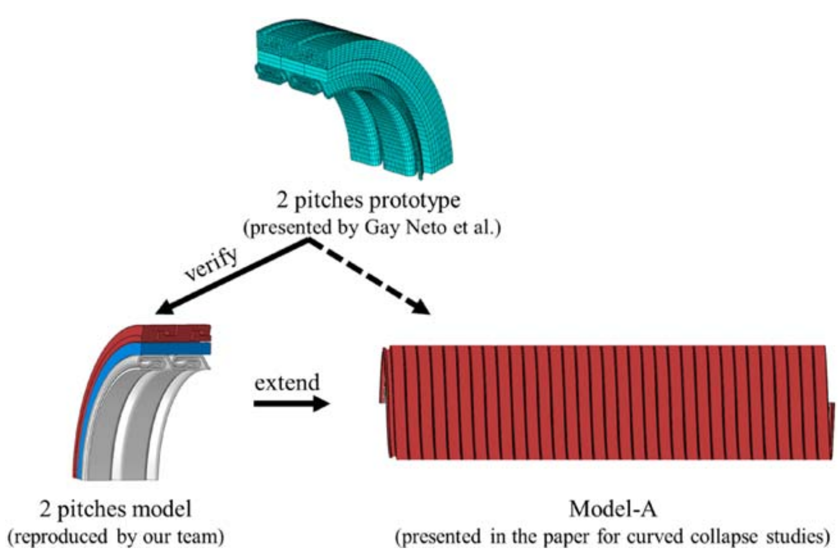

Figure 13. Verification procedure of Model-A. (This figure is available in colour online.)

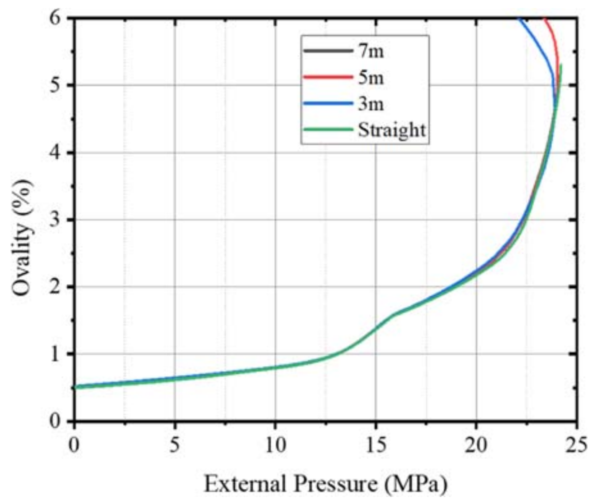

Figure 14. External pressure vs. ovality for Model-A with different pipe curvature. (This figure is available in colour online.)

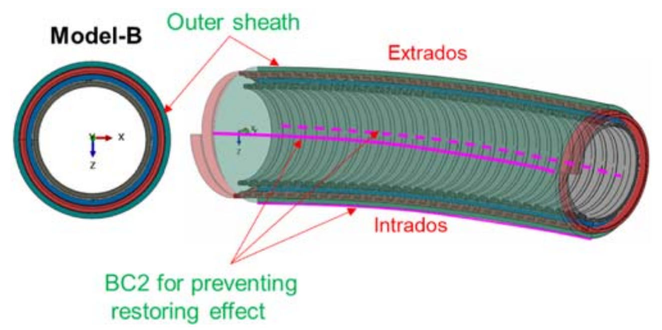

Figure 16. BC2 – fixed lines on the outer surface of the outer sheath for preventing restoring effect in Model-B. (This figure is available in colour online.)

to its MBR. On the side of pipe intrados, there was an obvious unclosed gap between the layers. This is abnormal since the curvature creates a dis-symmetry between the carcass intrados and extrados, making its extrados less stiff and easier to be deformed (Gay Neto et al. 2012; Clevelario et al. 2010). As a result, the external pressure forces the cross section of the carcass to form a symmetric shape rather than a bi-symmetric one. Considering BC1 in Model-A might interfere the collapse behaviour of the carcass, a better boundary condition for preventing the restoring effect was carried out in the following.

3.2. Improved boundary condition for preventing restoring effect

By referring to the work of Gay Neto et al. (2012), a four layers' model called Model-B was built, as shown in Figure 16. This model was improved from Model-A by adding an additional outer sheath. The function of the outer sheath in Model-B was only to maintain the pipe curvature in the collapse process, preventing the pipe model from being restored to straight configuration. BC1 was abandoned in Model-B. Instead, a boundary condition called BC2 was adopted as follows: two middle lines from the outer surface of the outer sheath, lying on the neutral plane, were only allowed to move along X-axis direction while one bottom line on the pipe intrados was fully fixed.

Since the wet collapse is a snap-through buckling issue, the carcass becomes extremely unstable when the external pressure is close to its collapse pressure. As a result, the increment of arc length becomes extremely small in some cases in order to seek for the convergence. This will require tremendous computational cost to reach the collapse pressure. To better utilise the computational resources, a minimum increment of arc length of 10^{-8} was set to automatically terminate the numerical analyses when such a situation occurred. For the cases with the terminations, their stress fields were extracted to evaluate whether they are close to collapse.

The stress distribution over the carcass at/ near the collapse limits from Model-A and Model-B are shown in Figures 17 and 18, respectively. From these two figures, it can be seen that the carcass collapses with a maximum von Mises stress that around 650 MPa. One exception is the 3 m case of Model-B, in which the maximum stress of the carcass is 643 MPa with an external pressure of 22.07 MPa. By referring to other cases, an extra external pressure of 0.2 MPa would be needed for the occurrence of collapse in this 3m case. For example, in the 7 m case of Model-B where collapse occurs, the external pressure goes up from 22.9 MPa with a maximum stress 645 MPa to 23.06 MPa with the collapse stress 652.6 MPa. From this perspective, the external pressure of 22.07 MPa in the 3m case of Model-B from its last analytical step is quite close to the actual collapse limit.

Table 4 lists the wet collapse pressure predicted Model-A and Model-B for each radius of curvature (∞ represents the straight riser). The results from Model-A and Model-B are very close for a straight riser, which indicated the newly-added outer sheath has little influence on the wet collapse

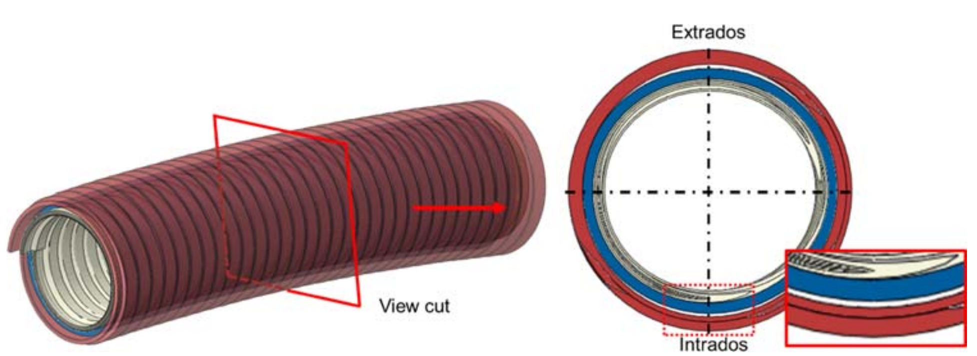

Figure 15. View cut – cross-sectional shape of Model-A with MBR at collapse moment. (This figure is available in colour online.)

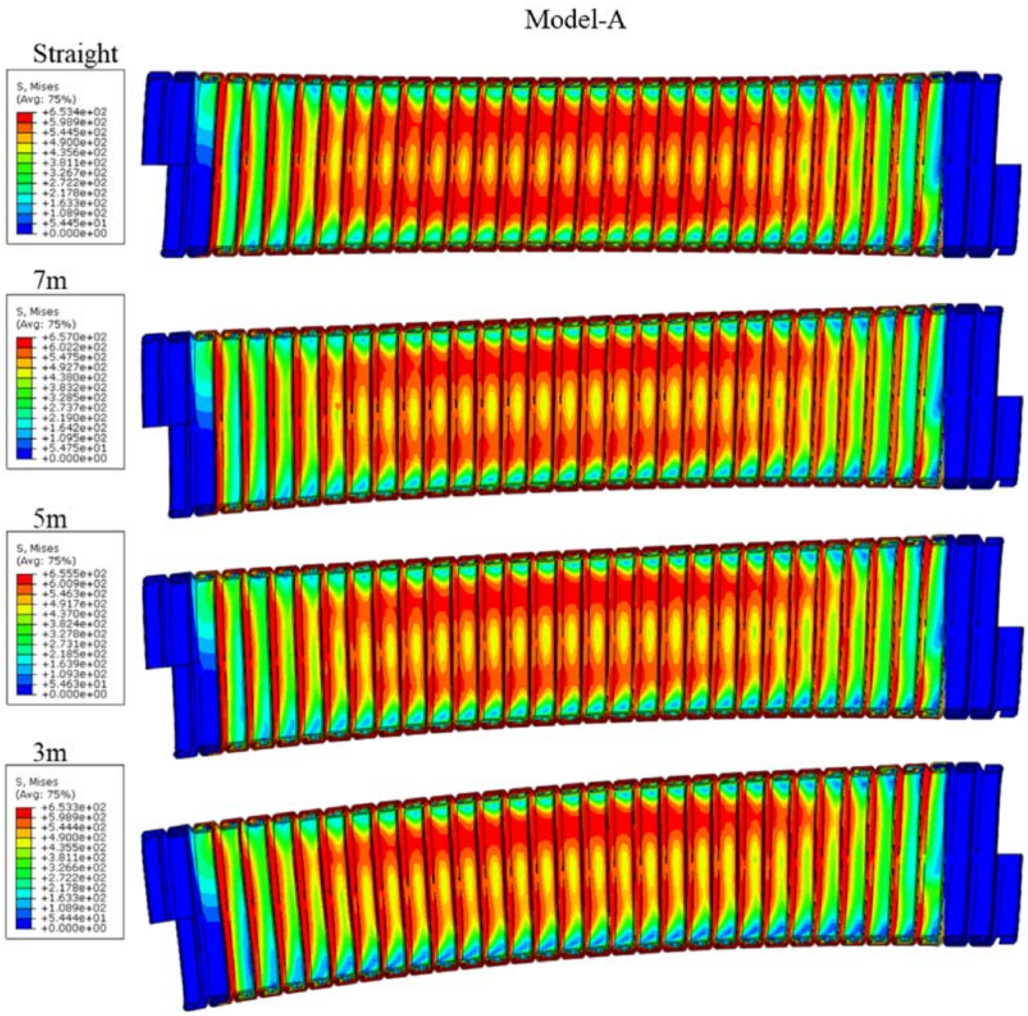

Figure 17. Stress distribution over the carcass at/ near the collapse limits from Model-A. (This figure is available in colour online.)

pressure. Figure 19 plots the curves of external pressure vs. pipe ovality given by Model-B for each radius of curvature. Discussion of those results are given in the following section.

4. Mechanism investigation based on the case results

In the section of case study, two FE models, Model-A and Model-B, were established. Model-A was a three-layer model with the carcass, the inner liner and the pressure armour. A boundary condition called BC1 was adopted in Model-A to prevent the restoring effect in curved collapse analyses, which was the nodes on the two lines of inner liner (see Figure 9) that were only allowed to move along X-axis direction after bending. However, it was noted that BC1 had an interference on the collapse behaviour of the carcass since the liner it was applied onto was a layer for transferring external pressure to the carcass. Therefore, Model-B was developed with an additional outer sheath, and BC2 replaced BC1 by moving the fixed lines to the outer surface of the outer sheath (see Figure 16).

Both Model-A and Model-B were employed to predict the wet collapse pressure of a 4″ ID flexible riser with an increased radius of curvature from ∞, i.e. straight, to 3 m, as listed in Table 4. For the straight riser, the predictions from these two models agree quite well with each other, indicating that the outer sheath in Model-B has little influence on wet collapse pressure. However, they performed different in the curved collapse analyses. This difference between the results from those two models was analysed to identify the curvature-induced factors for triggering the decrease of wet collapse pressure.

4.1. Investigation of the factors listed in literature

As mentioned above, two possible factors were given in public literature to explain the reduction of wet collapse resistance in curved flexible pipes. One is the squeeze effect from the bent liner, which could introduce an additional ovalization to the cross section of the carcass (Loureiro and Pasqualino 2012). The other is the pitch elongation due to bending (Gay Neto et al. 2012), which reduces the superposed area between two carcass profiles within one pitch (Gay Neto and Martins 2012), leading to a decreased radial stiffness on the carcass extrados. The influence of these two factors on the wet collapse pressure of curved risers were investigated by bending both Model-A and Model-B to their MBR (3 m).

To observe the squeeze effect, the ovalization of the carcass were calculated by measuring the internal maximum and

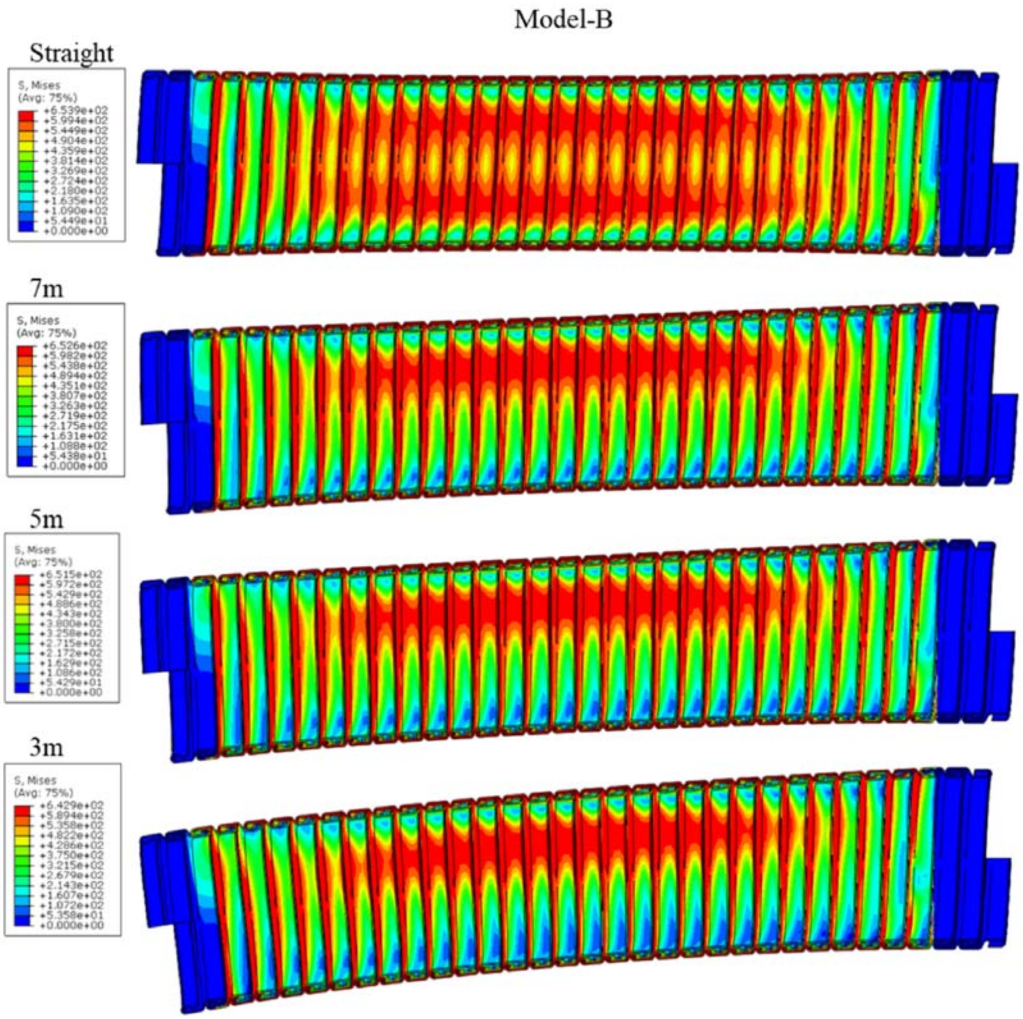

Figure 18. Stress distribution over the carcass at/ near the collapse limits from Model-B. (This figure is available in colour online.)

minimum pipe diameters, D_{I_max} and D_{I_min}, of the carcass before and after bending. With Equation (1), the ovalization of the carcass could be determined. The pitch of the carcass was also measured to reflect its change due to the bending. Those measurement were performed as illustrated in Figure 20, and the results are listed in Table 5.

According to Table 4, Model-A and Model-B have different performances on their curved wet collapse resistances. Compared to the straight one, there is a drop around 8–9 % of wet collapse pressure when Model-B is bent to MBR. In the same case study of Model-A, this drop is only 1.2%. However, the curvature-induced additional ovalization and pitch elongation in two models are almost the same. The additional ovalizations of the carcass caused by squeeze effect are quite close in both two models, which are around 0.023%, while the carcass pitches perform the exact same elongation. It indicates that the squeeze effect and pitch elongation can cause slight decrease of wet collapse pressure, but they are not the major factors for reducing the wet collapse resistance of the curved flexible risers.

Table 4. Wet collapse pressure predicted by Model-A and Model-B for each radius of curvature.

Curvature radius(m)		∞	7	5	3
Collapse pressure(MPa)	Model-A	24.21	24.07	24.04	23.92
	Model-B	24.23	23.06	22.82	22.07

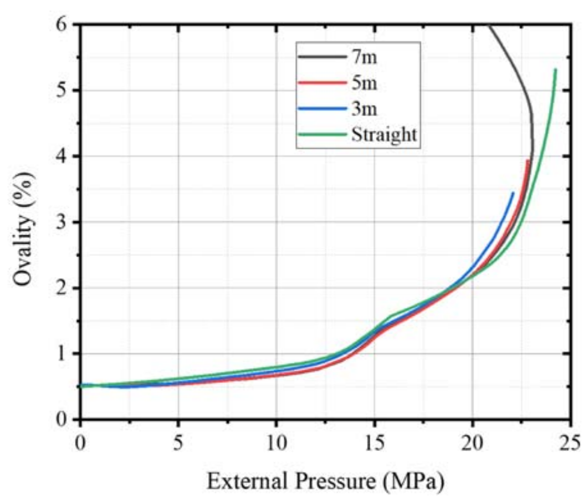

Figure 19. External pressure vs. ovality for Model-B with different pipe curvature. (This figure is available in colour online.)

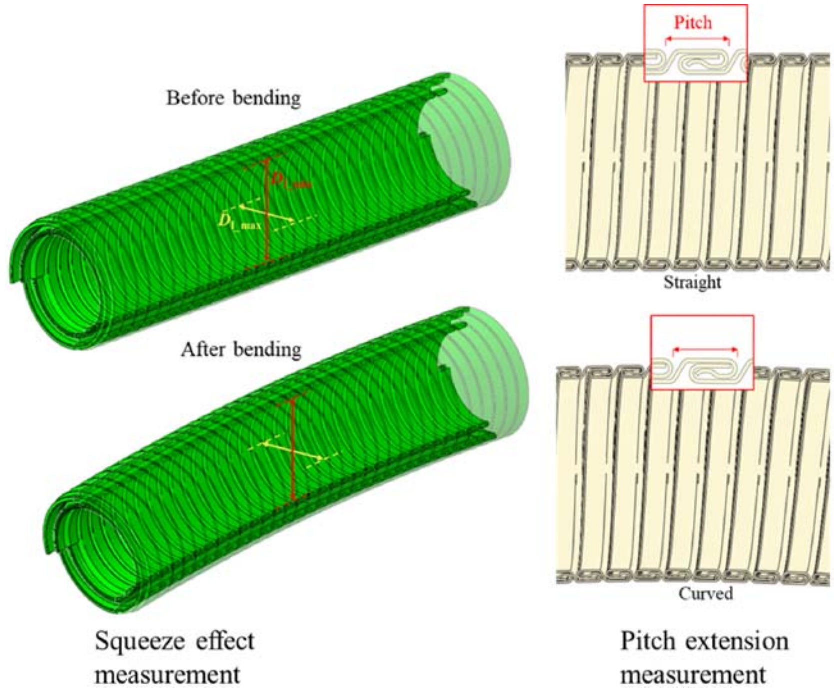

Figure 20. Measurement of the additional ovalization (left) and the pitch elongation (right) of the carcass before and after bending. (This figure is available in colour online.)

4.2. Dominant factor in curvature effect

As stated above, the application of BC1 in Model-A interfered the layer interaction during the collapse process, leading to incorrect prediction results. Therefore, Model-B was adopted to study the collapse behaviours of curved flexible risers. According to the results listed in Table 4, a significant reduction on the wet collapse pressure occurred after Model-B was bent to MBR. By observing the collapse behaviours of the curved Model-B, it was found that the carcass presented a symmetrical cross-sectional shape at its collapse region, as shown in Figure 21. This differs from the ones of Model-A, see Figure 15, which performed an approximate bi-symmetrical oval-shaped cross section even for MBR.

Figure 22 gives an illustration of these two oval-shaped cross sections by treating them as concentric rings. When the external pressure goes up, it forces parts of the carcass to detach from the inner surface of the pressure armour. Those detached portions of the carcass can be regarded as a circular arch with a new centre O' (Li et al. 2020), which has a rise *f*, the vertical distance between the separation points and crown, and a span *l*, the horizontal distance between its two separation points (Karnovsky 2011). The bi-symmetrical cross section of the carcass has two identical detached portion at its top and bottom while the symmetrical shape only has one detached portion. If the circumferential length of the carcass is assumed to remain unchanged during the collapse process, its detached arched portion performs a smaller rise-span ratio *f*/*l* in the symmetrical oval-shaped cross section. For the arch with a smaller rise-span ratio, a greater circumferential thrust can be triggered by the uniform radial external pressure, making the arch material easier to be plasticised (Timoshenko and Gere 1963; Coccia et al. 2015). As a result, a greater decrease of the collapse resistance occurs for the carcass in a symmetrical cross-sectional shape.

Since the curvature-induced pitch change causes a dis-symmetry of the radial stiffness on the carcass extrados and intrados, the cross-sectional shape of the carcass is then more close to a symmetrical one at the collapse moment. For the curved flexible riser, its wet collapse capacity is dominated by the buckling strength of the detached portion of the carcass extrados. Therefore, the rise-span ratio *f*/*l* of this detached portion

Table 5. Changes of ovalization and pitch of the carcass before and after bending.

Model Name	Status	Ovalization (%)	Carcass pitch (mm)
Model-A	Before bending	0.500	16.00
	After bending	0.524	16.32
Model-B	Before bending	0.500	16.00
	After bending	0.523	16.32

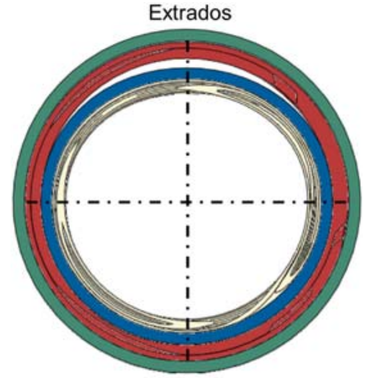

Figure 21. View cut – cross-sectional shape of Model-B with MBR at collapse moment. (This figure is available in colour online.)

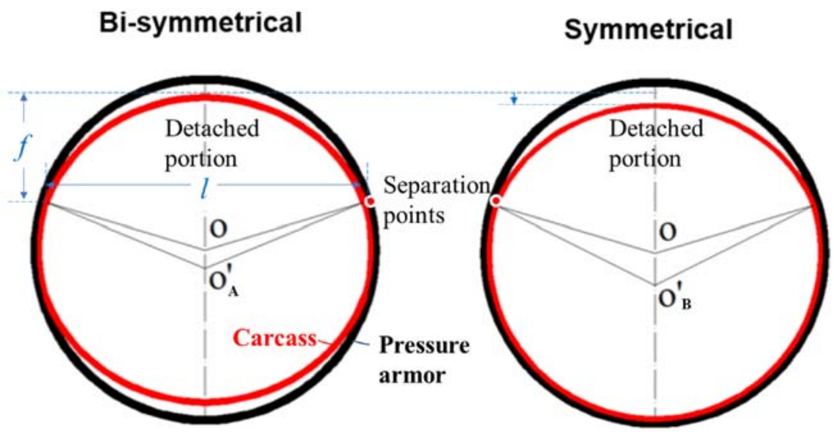

Figure 22. Bi-symmetrical and symmetrical shapes of the pipe cross section at the collapse moment. (This figure is available in colour online.)

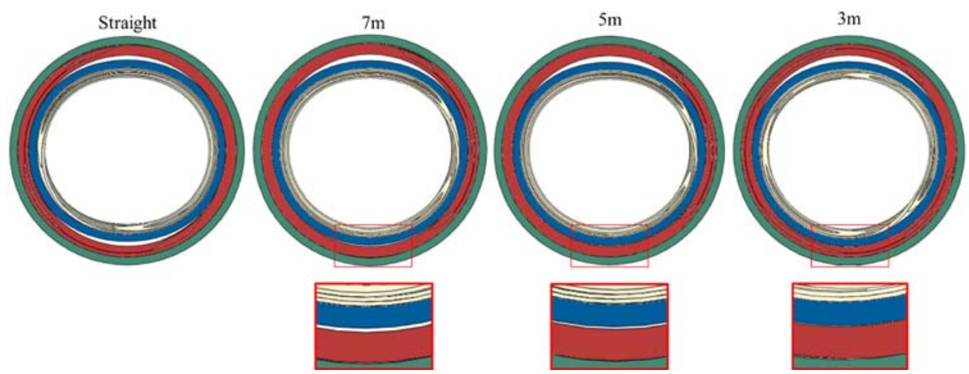

Figure 23. View cut – cross-sectional shapes of the doubly initial ovalized-carcass at collapse moment for different radius of curvature. (This figure is available in colour online.)

plays an important role in the collapse resistance. Figure 23 shows the cross-sectional shape of the carcass at the collapse moment for each radius of curvature, indicating that the rise-span ratio f/l of the detached portion decreases with the increase of pipe curvature. As a result, the wet collapse pressure of the flexible riser is heavily reduced when there is a large pipe curvature.

5. Conclusions

In this paper, mechanism studies were presented by sophisticated 3D FE models to investigate the curvature effect on the wet collapse behaviours of bent flexible risers. A three layers model called Model-A with a length of 30 carcass pitches was developed at first, which was made up of the carcass, the inner liner and the pressure armour. To prevent the curved models from restoring to straight configuration, a boundary condition called BC1 was adopted by fixing two lines on the outer surface of the liner. However, it was then found that BC1 interfered the collapse behaviours of the carcass while resisting the pipe restoring effect, leading to incorrect prediction of wet collapse pressure for curved risers. In view of this, a model called Model-B was built, which was improved from Model-A by adding an additional outer sheath. The function of this outer sheath was only to maintain the specified curvature in the collapse analysis.

Both two models were employed in the case studies. With this investigation, the main factors within the curvature effect are revealed for the first time. Based on this investigation results, conclusions can be drawn as follows:

(1) Pipe curvature has a significant reduction effect on the wet collapse pressure of flexible risers. When the riser was bent to its MBR, there was a drop around 8–9 % of wet collapse pressure in comparison with the straight one according to the results from Model-B.
(2) The deformed cross-sectional shape of the carcass during the collapse process is the dominant factor of curvature effect. The geometry of the detached portion on carcass extrados is influenced by pipe curvature. The flexible riser with a greater pipe curvature can lead to a more 'flat' detached carcass portion, turning this portion into an arch of a smaller rise-span ratio f/l. As a result, the collapse resistance of the carcass was reduced.
(3) Curvature-induced pitch elongation on the carcass extrados is one factor for reducing the wet collapse pressure. This elongation reduces the superposed areas between two carcass profiles within one pitch, making the carcass extrados less stiff and easier to be collapsed.
(4) Squeeze effect from the bent liner is another factor for reducing the wet collapse pressure. During the bending process, the flattened regions of the liner can squeeze

the carcass, imposing an additional ovalization onto it. Since riser model used in this study performed a small bending stiffness ratio of the liner to the carcass, the squeeze effect did not cause a significant additional ovalization. However, this effect could be enhanced if this bending stiffness ratio increases.

(5) Finite element analyses require very high computational cost for predicting the collapse pressure of flexible risers. Running one job on 2 nodes/32 cores with our HPC took 2–3 days on average. It spent more time if there was a convergence problem. For the collapse analysis in the design stage, this is less efficient to give designers the feedback.

The studies presented in this paper are going to serve our ongoing project, which aims to develop an efficient analytical model for the collapse analysis of flexible risers in design stage. The curvature-induced factors revealed in this paper will be introduced into this developing analytical model. For companies who are developing new riser product for ultra-deep water production, such an analytical model can facilitate their design stage.

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