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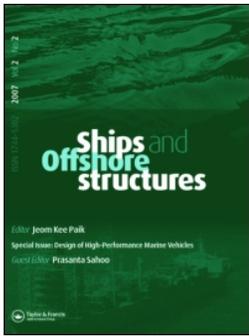
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Residual ultimate strength of offshore metallic pipelines with structural damage – a literature review

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ABSTRACT

The latest research progress on residual ultimate strength of metallic pipelines with structural damage is presented through literature survey. The investigated pipe diameter-to-thickness ratios majorly lie between 20 and 50, which are typically applicable in deep water. Influential parameters in terms of pipe load, installation process and material that affect the ultimate strength of pipes are categorised. Structural damage including dent, metal loss and crack is identified and efforts are made to summarise critical damage factors such as dent length and crack depth. Furthermore, research and prediction methods on pipe residual ultimate strength in terms of experimental tests, numerical simulations and analytical predictions are summarised and discussed. Specific details on how to introduce, simplify and simulate structural damage are presented and discussed. It is expected that the mechanism of residual ultimate strength of metallic pipes with structural damage can be clarified through this study so that guidance will be provided for researchers in this field.

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Metallic pipeline; residual ultimate strength; crack; dent; metal loss

Nomenclature

$\bar{\sigma}$	flow stress of material	D_{\max}	maximum outer diameter of pipe
δ	ovalisation of pipe	D_{\min}	minimum outer diameter of pipe
δ_0	initial ovalisation of pipe	E	Young's modulus
δ_{\max}	maximum ovalisation of pipe	h	depth of pipe wall thickness t subtracting the depth of metal loss d_m
λ	dimensionless length of dent, $\lambda = l_d/\sqrt{Rt}$	J	J integral
λ_{cl}	critical half-wave length	K	stress intensity factor
ν	Poisson's ratio	L	pipe length
ϕ	the angle of plastic neutral axis	l_d	dent length in pipe hoop direction
σ_l	membrane stress in pipe longitudinal direction	l_m	length of metal loss in pipe longitudinal direction
σ_u	the ultimate tensile strength of pipe material	M_c	limit bending moment of intact pipe
σ_y	material yield strength	M_f	bulging parameter
σ_θ	membrane stress in pipe hoop direction	M_y	plastic bending moment of intact pipe without material hardening effect
σ_{cbe}	elastic buckling stress under pure bending	M_{yh}	ultimate bending moment accounting for material hardening effect
σ_{cb}	busting stress of pipe	M_{ym}	residual ultimate bending moment of pipe with metal loss
σ_{eng}	engineering stress of material	n	material constant
σ_h	ultimate strength of pipe in hoop direction	P_b	critical bursting pressure of pipe
σ_{long}	ultimate strength of pipe in longitudinal direction	p_i, p_e	pipe internal pressure, external pressure
σ_{true}	true stress of material	P_{ce}	external buckling pressure of pipe
ε_c	limit pipe strain under pure bending	P_{ee}	external buckling pressure of pipe in elastic domain
ε_{eng}	engineering strain of material	P_{ye}	critical external pressure at material yielding point
ε_{true}	true strain of material	Q	correction factor of metal loss
a_1, a_2, a_3, a_4	correction parameters	R	pipe average radius
A_e	cross-sectional area under external pressure	S_{eff}	effective axial force
A_i	cross-sectional area under internal pressure	t	pipe thickness
c_1, c_2	correction parameters		
D	outer diameter of pipe		
d_d	dent depth		
d_m	depth of metal loss		
D_{ave}	average outer diameter of pipe		

T_c	ultimate tension force subjected to uniaxial tension
T_{ya}	plastic axial force
y_{comp}, y_{tens}	force arms

1. Introduction

As the demand for energy increases, the exploitation of oil and gas is becoming increasingly important. They remain dominant energy sources in the foreseeable future according to BP Energy Outlook (BP 2012). By 2030, the consumption of oil and gas will be over eight billion tons (over half of the world's entire energy consumption). So far, the depletion of fossil fuel onshore has forced people to explore new offshore fields for more energy resources. However, the transportation of oil or gas in rough sea environments has become a major challenge. One of the most reliable solutions is to use pipelines, as seen in Figure 1, which shows the typical configuration of offshore pipelines associating with platforms and wells. The petroleum industry has proven that pipelines are one of the most economical ways to transport crude oil and natural gas across extensive regions.

In harsh sea environments, sufficient structure strength is necessary in order to guarantee the safety and integrity of pipelines, which depends on good design, strict quality control and standard operation. However, like any engineering structures, pipelines do occasionally fail due to structural damage. Two main causes of structural damage that could induce pipeline failure are: mechanical interference and corrosion. It has been estimated that the failure of oil and gas transmission pipelines resulting from mechanical damage ranges from 55% in the USA to around 70% in Europe (Ghaednia et al. 2015b). Dents, gouges, cracks, corrosion and combinations thereof are commonly found on pipelines. They might be caused by abnormal or accidental events including dropped objects, dragging anchors, fishing equipment, sinking vessels, mudslides and harsh environments such as extreme waves and currents (Bjørnøy et al. 2000; DNV 2010; Abeele et al. 2013; Ghaednia et al. 2015b). Under these circumstances, prediction of the strength of a pipeline is a subject that has attracted the attention of many researchers such as Dyau and Kyriakides (1993), Lancaster and Palmer (1996a), Park and Kyriakides

(1996), Estekanchi and Vafai (1999), Bjørnøy et al. (2000), Bruschi et al. (2005), Vitali et al. (2005), Vaziri and Estekanchi (2006), Bartolini et al. (2014), Ghaednia et al. (2015a), Ghaednia et al. (2015b) and Rajabipour and Melchers (2015). Relevant research can not only clarify the inner mechanism of the pipeline structure failure, but also facilitates the decision-making in engineering practice when pipelines undergo structural damage.

Considerable research such as Yeh and Kyriakides (1986), Yeh and Kyriakides (1988), Park and Kyriakides (1996), Vitali et al. (2005) and Mohd et al. (2015) has been conducted on the residual ultimate strength of offshore metallic pipelines. Critical parameters that would affect the pipeline strength include the diameter-to-thickness ratios (D/t), length-to-diameter ratios (L/D), material properties, load conditions, manufacturing processes, initial imperfections and residual stress. A pipeline is generally considered as a thin-walled shell structure when the D/t ratio is larger than 20. The common transmission pipes in deep water have D/t ratios between 25 and 30, while much larger D/t ratios are employed in shallow water (Fyrileiv et al. 2013; Guo et al. 2013). The D/t ratio governs the pipe failure. For instance, elastic-plastic collapse generally occurs on thick-walled pipes when the D/t is less than 20, while elastic buckling failure generally happens on pipes when the D/t is larger than 40 (Fyrileiv et al. 2013). A combined failure mode would occur on the structures with ratios between 20 and 40. The length-to-diameter (L/D) ratio would also affect the behaviour of the structure strength under certain situations, such as pipes subjected to pure axial load (Zingoni 2015).

Additionally, the loading conditions of offshore pipelines vary under different scenarios. For shallow water (water depth less than 300 m), the dominant load is internal pressure and over-internal pressure could lead to bursting (EIA 2010). The past few decades have seen considerable research such as Fu and Kirkwood (1995), Estekanchi and Vafai (1999), Loureiro et al. (2001), Kim et al. (2002), Benjamin and Andrade (2003), Vaziri and Estekanchi (2006), Levold et al. (2013), Levold, Restelli et al. (2013), Ghaednia et al. (2015a) and Ghaednia et al. (2015b), on the bursting capacity of pipelines subjected to internal pressure. With the exploration of energy into deep water (water depth between 300 and 1500 m) or ultra-deep water (water depth greater than 3000 m), the load is gradually dominated by external hydro-static pressure and the buckling collapse could occur as a result of over-external pressure. Likewise, a considerable amount of research such as Dyau and Kyriakides (1993), Park and Kyriakides (1996), Gresnigt et al. (2000), Bruschi et al. (2005), Gong et al. (2013) and Zhang et al. (2015) has been carried out on the buckling collapse capacity of pipelines. Meanwhile, the bending moment exists extensively in pipes. For instance, pipes are exposed to a large bending moment when they are leaving a barge during the pipe installation phase (Gresnigt et al. 2001; Vitali et al. 2005; Netto et al. 2006; Hilberink 2011; Levold et al. 2013; Levold, Restelli et al. 2013). The manufacturing process is another factor that has a considerable effect on pipe strength. Two typical types of pipelines exist: seamless pipes and pipes with a longitudinal or spiral-welded seam. The former type is produced without a seam or only welded in the hoop direction. Thus, the material properties of pipes have not been significantly affected. The latter are

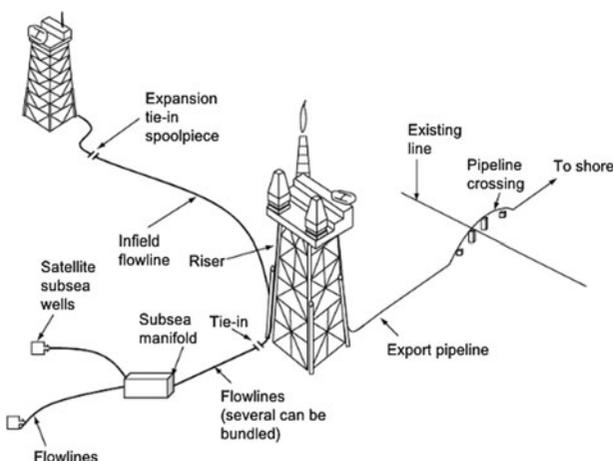


Figure 1. The typical configuration of offshore pipelines associating with platforms and wells (Guo et al. 2013).

generally produced by the UOE (U-ing, O-ing, and expanding) process (Gresnigt et al. 2000, 2001), which is a common manufacturing method for large-diameter pipelines. During such process, the prepared plate is first formed into a U-shape by a special press. Then, through an Oing-press, it is formed into a circular shape. The ‘Bauschinger effect’ (Gresnigt et al. 2000; Bruschi et al. 2005; Vitali et al. 2005; DNV 2013b; Polenta et al. 2015), therefore, could be activated, which decreases the material yield stress when the loading direction has been changed. The reduction ratio of material compression yield stress can reach up to 30% of the un-processed material value (Tam et al. 1996; Bruschi et al. 2005; DNV 2013b). Therefore, materials are no longer isotropic and will cause large discrepancies in the prediction of pipe strength.

Structural damage such as dent, metal loss and crack has effect on pipe strength, which may cause detrimental structure failure. Thus, it is important to investigate the residual ultimate strength of damaged pipelines under these circumstances. Research on damaged pipes can be seen in the literature such as Park and Kyriakides (1996), Starnes and Rose (1998a), Estekanchi and Vafai (1999), Gresnigt et al. (2001), Macdonald and Cosham (2005), Vaziri and Estekanchi (2006), Gresnigt et al. (2007), Kim et al. (2013), Bai and Bai (2014b), Mohd et al. (2014), Ghaednia et al. (2015a, 2015b) and Lee et al. (2015). Park and Kyriakides (1996) experimentally studied the collapse resistance capacity of cylinders with a single dent under external pressure. Starnes and Rose (1998a, 1998b) investigated the non-linear buckling behaviour of thin-walled cylinders with a longitudinal crack subjected to combined loads. Macdonald and Cosham (2005) conducted a detailed literature review about the effect of dent and gouge damage on pipeline structures. Vaziri and Estekanchi (2006) numerically studied the buckling behaviour of a cracked cylinder subjected to combined internal pressure and axial force in a linear domain. The effect of crack type, length and orientation was accounted for. It was found that a crack might significantly alter the buckling behaviour of cylindrical shells by provoking local buckling modes. And the internal pressure could either stabilise the shell and increase the buckling capacity by suppressing the low level buckling modes or provoke local buckling due to stress concentration depending on the crack orientation and loading parameters. Ghaednia et al. (2015a, 2015b) investigated the effect of dent and crack damage on the burst capacity of a pipeline. Lee et al. (2015) carried out numerical simulations on the burst capacity of pipeline elbow with metal loss.

To investigate the strength of pipeline structures, research methodologies are typically categorised into experimental tests, numerical simulations and analytical predictions. Experiments from the literature such as Dyau and Kyriakides (1993), Fu and Kirkwood (1995), Park and Kyriakides (1996), Lancaster and Palmer (1996a), Gresnigt et al. (2000), Bjørnøy et al. (2000), Gresnigt et al. (2001), Loureiro et al. (2001), Kim et al. (2002), Benjamin and Andrade (2003), Vitali et al. (2005), Bruschi et al. (2005), Netto et al. (2006), Hilberink (2011), Levold et al. (2013), Levold, Restelli et al. (2013), Polenta et al. (2015) and Zhang et al. (2015) have been carried out. When tests are not available, a good alternative is the FEM (finite element method), which has been extensively deployed by researchers and recognised as a powerful tool that can provide accurate prediction of structure

strength. Some so-called ‘numerical laboratories’ for predicting pipe strength have been developed by research groups (Bruschi et al. 2005; Vitali et al. 2005; Gresnigt et al. 2007; Bartolini et al. 2014). Reliable prediction results have been obtained compared with test results in terms of the shape of buckling modes and the relation between bending moment and curvature (Zhou & Murray 1993; NEB 1994; Bruschi et al. 1994; Kirkwood et al. 1996; Park & Kyriakides 1996; Batte et al. 1997; Loureiro et al. 2001; Kim et al. 2002; Benjamin & Andrade 2003; Jin & Shao 2004; Bruschi et al. 2005; Netto et al. 2006; Levold et al. 2013; Levold, Restelli et al. 2013; Bartolini et al. 2014; Chen et al. 2015; Ghaednia et al. 2015b). Based on experimental and numerical research, considerable data have been integrated into engineering practice in the form of industrial standards, for instance ASME B31G (ANSI 1991; Szary 2007), Shell 92 (Klever et al. 1995), DNV-RP-F101 (DNV 2004), BS7910 (BSI 2005), etc.

The objective of the current paper is to present the latest research progress in residual ultimate strength of offshore metallic pipelines based on a literature review. In Section 2, we identify the typical loading conditions of offshore pipelines and in Section 3 we categorise the damage types. Their effects on pipe ultimate strength are summarised and discussed. The experimental and numerical methods for pipe strength investigation are discussed in Sections 4 and 5, respectively. Pipe tests in terms of buckling, elastic–plastic failure and structure collapse are summarised. Some common approaches for introducing damage under laboratory condition are summarised. Influential parameters in FEA (finite element analysis) related to offshore pipelines, such as mesh, material properties and boundary conditions are also identified. In Section 6, we summarise the analytical method for pipe strength prediction such as typical empirical equations. The paper ends with some concluding remarks.

2. Category of pipe loads

Load conditions on offshore pipelines are complex and vary with specific installation methods and pipe phases. A summary of typical load conditions for offshore pipelines is presented in Table 1. Generally, a combination of loads, including bending moment, internal/external pressure, lateral load and axial force, are exerted on pipe structures for the majority of situations, but the dominant load is changing and could induce different types of structure failure. For instance, external pressure becomes dominant during a dry installation in deep water (Guo et al. 2013). Another example is that, during the hydrotest phase before operation, pipe structures suffer from high internal pressure up to 1.25 times of the design internal pressure (DNV 2013a), which is used to check the structure integrity. As a result, internal pressure becomes dominant. Meanwhile, with the variation of ocean environments such as uneven sea bottoms and mudslides, and collision with foreign objects such as anchors and fishing boats, the dominant load changes as well. Therefore, it makes sense that investigations of pipe strength should be accompanied by careful checks of load conditions. In this section, we start by summarising and discussing specific installation methods, and then identify typical load conditions.

Table 1. A summary of load condition for offshore pipelines.

Load type	Installation phase		Test phase		Operation phase	
	Shallow water	Deep water	Shallow water	Deep water	Shallow water	Deep water
Bending moment	++++ ^a	+++	/	/	++	++
Axial force	++	++	+	+	+	+
Internal pressure	+	+	+++	+++	+	+
External pressure	+	+++	+	+	+	++
Others (lateral force)	/	/	/	/	+++	+++

^aThe number of '+' denotes the significance of specific load.

Three typical pipeline installation methods are S-lay, J-lay and reel lay (Kyriakides & Corona 2007; Hilberink 2011), as seen in Figure 2. The S-lay installation method is suitable for installation in shallow water and can lay pipes up to 6.5 km/day (Kyriakides & Corona 2007). As illustrated in Figure 2(a), the bending moment in S-lay becomes dominant. Since long stinger and large tensioner are needed, the S-lay method is not suitable for installation in deep water. The tensioner and stinger are required in order to reduce the bending moment. Before installation, each pipe segment is welded, inspected and coated, station by station on board. The integrated pipe will then leave the vessel at the stern, pulled by a tensioner and supported by a stinger so that the bending curvature of pipes is strictly controlled. Afterwards, the pipe will be bent in the opposite direction due to its own gravitation, which forms a sagbend shape.

These excessive bending moments might cause structure failure such as buckling, elastic–plastic failure and even fracture failure.

While the S-lay method is only suitable for shallow water, the J-lay method can be used in deep water. This is because, based on J-lay, a relative short suspending length and less pre-tension force are required. The installation occurs in a nearly vertical way, with the pipe laid down on seabed with only one sagbend radius, as illustrated in Figure 2(b). The laying speed is up to 3.2 km/day (Kyriakides & Corona 2007). During installation, each pipe segment is first raised up to a vertical tower and then welded with each other. Likewise, the inspection and coating processes are carried out on board. By moving the vessel forward, the pipe is then laid down on the seabed. Since there is only one sagbend during installation, unlike the S-lay method, the risk of structure failure due to over-bending decreases.

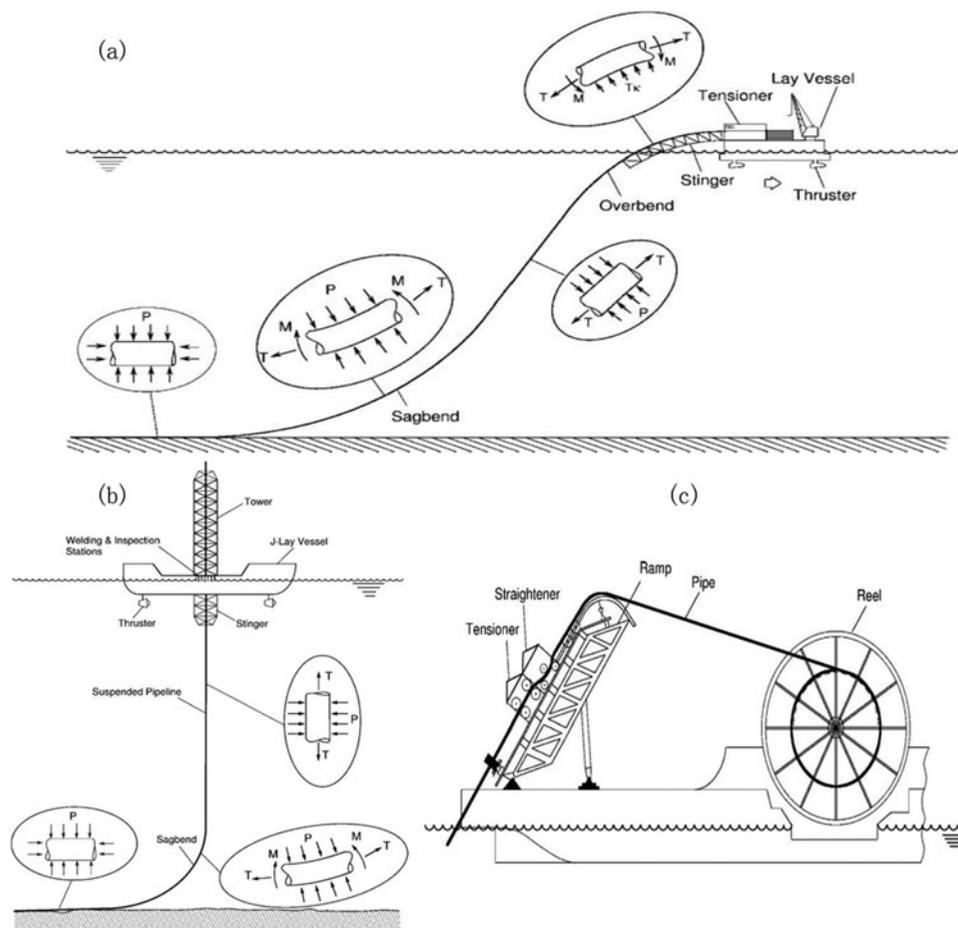


Figure 2. The typical pipe installation methods and corresponding loading conditions (Kyriakides & Corona 2007): (a) S-lay; (b) J-lay; (c) reel-lay.

However, possible structure failure such as buckling, elastic-plastic failure and fracture failure could occur due to the increase of water depth and installation complexity.

The reel-lay method is considered the most efficient installation method with a laying speed up to 3.5 km/hour (Kyriakides & Corona 2007). It is suitable for pipes with diameter smaller than 18 inches and a diameter-to-thickness ratio (D/t) between 20 and 24 (Fyrileiv et al. 2013). The main advantage of the reel-lay method over the other two methods is that the entire fabrication procedure including welding, inspection and coating is conducted onshore instead of offshore, which has largely reduced installation time and costs. Before installation, the pipes are spooled on a large diameter reel, which is mounted on a vessel as illustrated in Figure 2(c). During installation, the pipe segment is gradually unspooled by the reel and the pipes are plastically deformed and strengthened with multiple bending cycles. Therefore, large ovalisation of the pipe cross section will be induced. Loss of material yield strength in the localised region will occur due to the 'Bauschinger effect'. In general, the bending moment dominates the strength behaviour in reel-lay installation.

As discussed above, axial load is important in pipeline installation. However, it becomes complex and even controversial when it comes to the practical design. As a global force, pre-tension can not be directly switched to local axial force when investigating a single pipe segment. Instead, equivalent transformation should be carried out to define a specific axial force. In DNV standards (DNV 2007, 2013a), it has been defined as the effective axial force S_{eff} and expressed as Equation (1), where N is the true wall axial force, A_i and A_e are pipe cross-sectional areas under internal pressure and external pressure, respectively, p_i is the internal pressure and p_e is the external pressure. Many researchers such as Carr et al. (2003), Galgoul et al. (2004), Fyrileiv and Collberg (2005) and Vedeld et al. (2014) have argued against this concept because it is somewhat counter-intuitive. For instance, based on this definition, a closed pipe segment subjected to internal pressure could buckle when the pressure builds up. However, this concept has been demonstrated and widely used in engineering practice. Based on this definition, the axial force of pipe segments can be easily obtained as long as the pipe longitudinal strain is known. The effect of internal/external static water pressure has been directly accounted for.

$$S_{\text{eff}} = N - p_i A_i + p_e A_e \quad (1)$$

3. Category of pipe damage

In offshore pipelines, the main damage types are dent, metal loss, crack and combinations thereof. These types of damage could significantly affect the pipe strength, which might cause detrimental structure failure. In this section, we categorise the structure damage and summarise its effects on pipe strength. We also discuss common methods for introducing pipe damage under laboratory conditions.

3.1. Dent

A dent (Cosham & Hopkins 2004; Macdonald & Cosham 2005) is a permanent plastic deformation on pipe wall that produces a

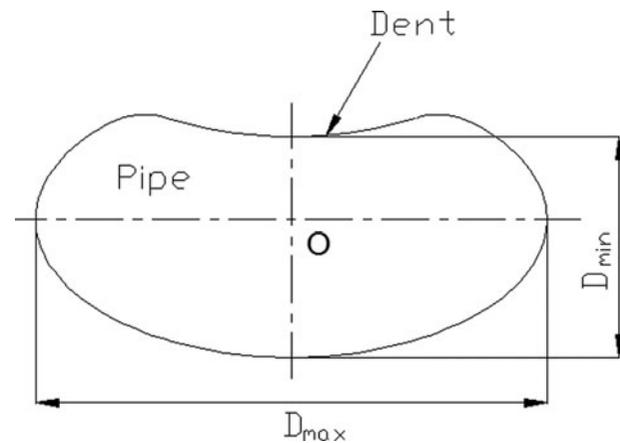


Figure 3. The sketch of an indenter-induced dent on metallic pipe.

gross distortion of the pipe cross-section, as seen in Figure 3. It might be caused by contact with foreign objects such as rocks, anchors or fishing trawl boards (Park & Kyriakides 1996; DNV 2010). Local buckling might be initiated by dents. Even worse, the global buckling of pipelines could be induced with catastrophic effects (Kyriakides & Babcock 1983). Based on the reviewed literature, the dents on pipelines can be categorised as follows:

- plain dent: a dent with smooth curvature variation but without wall thickness reduction and other defects.
- kinked dent: a dent that causes an abrupt curvature variation of a pipe wall.

The majority of research has focused on the effect of plain dents (Dyau & Kyriakides 1993; Park & Kyriakides 1996; Bjørnøy et al. 2000; Ghaednia et al. 2015a, 2015b) whereas few studies have looked at the behaviour of pipelines with kinked dents. The stress distribution and strength will be affected by the occurrence of dents, and the influential level depends on the different types of dominant load. For pipes under internal/external pressure, the dent depth is considered a significant influential factor, while its profile is not as critical as dent depth as long as the dent is a plain type (Seng et al. 1989; Beller et al. 1991; Ong et al. 1992; Lancaster & Palmer 1996a, 1996b). As Park and Kyriakides (1996) stated, the 'collapse capacity of pipes was relatively insensitive to the detailed geometry of a dent such as shape and size but to be critically dependent on the maximum ovalisation of its most deformed cross-section'. The ovalisation parameter δ (ABS 2001; DNV 2013a) is used to denote the severity of a dent, as shown in Equation (2). D_{max} , D_{min} and D_{ave} are the maximum, minimum and average outer diameter of deformed cross section, respectively, as illustrated in Figure 3. When the ovalisation parameter is small, the effect of dent on collapse performance of pipeline subjected to external pressure is quite benign. In contrast, large ovalisations significantly reduce the strength. As specified in DNV standard for offshore pipelines (DNV 2013a), a minimum ovalisation (0.005) must be introduced to any structures during calculation in order to account for its effect. An alternative way to denote dent severity is to directly use the ratio between dent depth and pipe diameter D . For pipe burst capacity under internal pressure, the upper limits of accepted dents in

terms of depth proportion have been proposed; for instances, 8%D from British Gas (Hopkins et al. 1989, 1992), 10%D in PDAM (Cosham & Hopkins 2004; Macdonald & Cosham 2005), 6%D from ASME B31.8 (ANSI 1991) and DNV (DNV 2010, 2013a). For dented pipes subjected to bending moment, few criteria have been found so far according to literature survey. However, it is widely accepted that combined dent and other defects such as metal loss and crack are more detrimental than single structural damage, which could largely reduce pipeline residual strength (Dyau & Kyriakides 1993; Park & Kyriakides 1996; Lancaster & Palmer 1996a; Bjørnøy et al. 2000; Ghaednia et al. 2015a, 2015b).

$$\delta = \frac{D_{\max} - D_{\min}}{D_{\text{ave}}} \quad (2)$$

In order to introduce a dent in laboratory environment, two conditions are generally accounted for based on engineering practice. The majority of dents are introduced into pipe without prescribed internal pressure (Fowler et al. 1994; Lancaster & Palmer 1996a; Alexander & Kiefner 1997; Bruschi et al. 2005; Vitali et al. 2005; DNV 2013a; Polenta et al. 2015). A few are introduced with prescribed internal pressure (Lancaster & Palmer 1996a; Vitali et al. 2005; Polenta et al. 2015; Ghaednia et al. 2015b), which is more close to the reality. According to the research of Gresnigt et al. (2007), the presence of internal pressure has a significant effect on the denting procedure and will largely increase the denting force for developing the same dent size. It should be noted that a spring-back phenomenon (Cosham & Hopkins 2004) is always associating with the denting process and its effect should be accounted for in either a test or a numerical simulation (Cai et al. 2016). Spring-back is defined as the bounce-back of the elastic part of the structure deformation. The spring-back ability of a dent mainly depends on the pipe material property, pipe geometry, dent shape, and whether the pipe is pressurised in advance or not.

3.2. Metal loss

Metal loss is a generalised kind of structural damage that involves partial loss of material in the form of gouges, notches, etc. Research such as Fu and Kirkwood (1995), Loureiro et al. (2001), Kim et al. (2002), Benjamin and Andrade (2003), Netto et al. (2006), Levold et al. (2013) and Levold, Restelli et al. (2013) has been conducted on the effect of single metal loss damage. Specifically, Levold et al. (2013) investigated the residual bending capacity of pipelines with corrosion-induced metal loss on a pipe's internal surface, where the internal pressure and axial tension force were prescribed in advance.

A gouge or a notch (Lancaster & Palmer 1996a; Macdonald & Cosham 2005) is a typical metal loss pattern, which has a regular profile but will not change the shape of pipe cross-section, as seen in Figure 4; they are usually fabricated under laboratory environment during experimental research. Corrosion (Fyrileiv et al. 2013; Levold et al. 2013; Zecheru et al. 2015) is generally considered the major cause of metal loss in offshore pipelines. Contact with sharp foreign objects such as anchor and fishing board that have scraped partial material out of the pipe is another common situation for pipe metal loss. Metal loss reduces the bursting and fatigue strength of the

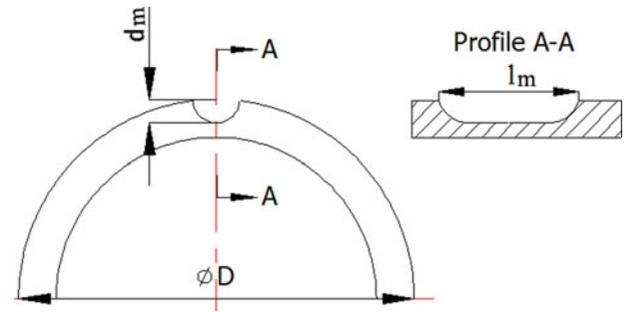


Figure 4. The sketch of metal loss on metallic pipe.

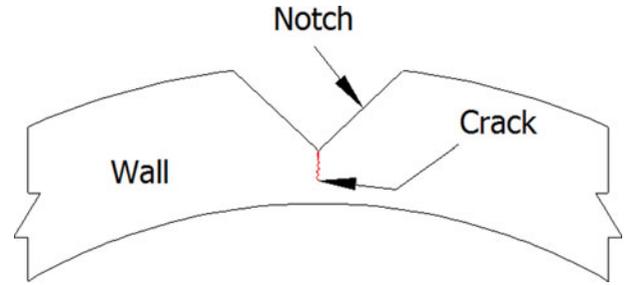


Figure 5. The sketch of crack at the V-notch tip on a metallic pipe.

pipe. A longitudinally orientated gouge is considered the most severe condition for internal pressure loading (Macdonald & Cosham 2005). Several parameters such as metal loss shape, length, width and depth are used to express a metal loss. In the design standard from DNV (DNV 2004), metal loss profiles are normally idealised as parabolic, rectangular or exponential type. However, different shapes did not make a significant difference to the effect of pipe residual ultimate strength. The metal loss depth is a critical parameter, as stated in the bursting strength research from Lee et al. (2015). Fracture failure might be initiated in the metal loss region, which can be denoted by a so-called 'notch stress-intensity concept' (Pluvinage 2006).

In order to introduce a prescribed metal loss under laboratory environment, the electro-discharging machining method (Levold et al. 2013; Ghaednia et al. 2015b) is generally deployed with specified types of electrodes. Alternatively, the machining method by deploying customised cutting tools is used to fabricate metal loss with different size, angle, shape and location.

3.3. Crack

A crack, as shown in Figure 5, is a kind of structure damage that is easily initiated within a structural region with defects such as welding. It can be introduced due to impact scenarios and/or the exposure to the corrosive environment and/or the cyclic loading arising from the pressure fluctuations and geologic movements (Cheng 2013; Ghaednia et al. 2015a, 2015b). Some chemical contents such as hydrogen gas can even speed up the occurrence of cracks at corrosion sites (Fassina et al. 2012). Cracks in pipelines may significantly compromise the buckling behaviour, jeopardise the structural integrity and induce detrimental structure failure (El Naschie 1974; Barut et al. 1997; Vaziri & Estekanchi 2006). Generally, two types of crack can be categorised in practice: one is a through-crack, while the other is a surface crack. From the engineering perspective, surface

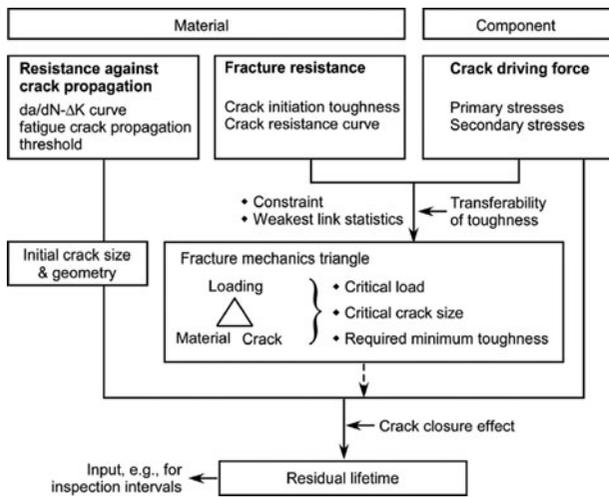


Figure 6. The schematic principle of fracture mechanics analysis (Zerbst et al. 2014).

cracks on pipe structures are strictly detected and prohibited during the fabrication stage, let alone through-cracks. However, they could occur during installation and operation stages due to some abnormal factors.

From the perspective of fracture mechanics, a general scheme of safety assessment on cracked structures is illustrated in Figure 6. It has clearly illustrated the relationship between different critical states in terms of the critical loads, the critical crack size, the required minimum fracture toughness and the residual lifetime due to crack propagation. In linear elastic domain, the stress intensity factor (K) can be well used to denote the crack characteristics (Riks et al. 1992; Anderson & Anderson 2005). In elastic-plastic domain, the CTOD (crack tip opening displacement) or J integral has been widely accepted to denote the cracks, although they have not been strictly proved by theorems (Anderson & Anderson 2005). The so-called CDF (crack driving force) and FAD (failure assessment diagram) (BSI 2005; API579 2007) approaches have been used for fracture assessment. In FAD method, a failure curve is used to assess the failure zone, safe zone and the security and safety factors (Pluvigne 2006). And it takes into account all kinds of failure: elastic collapse, brittle fracture and elastic-plastic failure. Therefore, careful attention should be paid to the occurrence of crack on structures during the residual ultimate strength investigation. One typical parameter of surface crack is the crack depth, which will largely compromise the structural capacity. Studies (Ghaednia et al. 2015a) have shown that once the crack depth exceeds a certain limitation – for example, a 4 mm crack depth in a pipe with 8.5 mm thickness – the bursting capacity of pipes subjected to internal pressure can be reduced by 38%. However, a shallow surface crack might not affect the pipe strength as demonstrated by Ghaednia et al. (2013, 2015b): when a crack depth is less than 2 mm in a pipe with 8.5 mm wall thickness, it did not affect bursting capacity at all. When the depth of pipe surface crack is less than 12.5% D , the crack can be physically removed by grinding in advance so that its effect on structural strength can be eliminated (Lancaster & Palmer 1996a; Bjørnøy et al. 2000; CSA 2011). Few studies have addressed the buckling strength of a cracked pipe subjected to external pressure or

Table 2. A summary of critical parameters in existing bursting tests.

S.N	Parameters	Domain
1	Outer diameter D (mm)	100–810
2	Wall thickness t (mm)	1–20
3	D/t	27–54
4	L/D	3–6.5
5	Materials	Steel, Al
6	Dent direction	Longitudinal, hoop (rare)
7	d_d/D (%)	5–28
8	d_m (mm)	2–10
9	d_m/t (%)	9–70
10	I_m/D (%)	15–76
11	Failure location	Damaged region

bending moment. Therefore, the effect of a crack on pipe residual ultimate strength, especially the combined damage with a crack, should be quantitatively investigated in order to obtain a deep view on the crack effect.

4. Experimental methods for strength evaluation

Experimental test is a traditional and reliable way to evaluate strength. A successful test is often contributed by the joint efforts of personnel including engineers, technicians, researchers and workers. Significant endeavour should be involved for test including test design, specimen fabrication, facility installation, data collection, data processing and even project management.

As we have mentioned in Section 1, the critical factors that affect the pipe strength include geometrical dimensions, material properties, load conditions and initial imperfections. Therefore, before a pipe test, comprehensive considerations are required to include or exclude those factors so that the authentic physical characteristics of a test will be revealed. For instance, the geometrical dimensions including pipe length, diameter and wall thickness are often measured carefully in a test in order to eliminate the effect of geometrical discrepancy. Material tensile tests are generally performed in advance in order to eliminate the material effect, which will also facilitate the development and validation of FEA models. Several material tensile tests of pipes can be seen from Bjørnøy et al. (2000), Vitali et al. (2005), Ghaednia et al. (2015a, 2015b), etc.

4.1. Bursting test of pipe

The bursting capacity of pipes subjected to internal pressure has attracted considerable interest from researchers. The literature review revealed several pipe tests from Fu and Kirkwood (1995), Lancaster and Palmer (1996a), Loureiro et al. (2001), Kim et al. (2002) and Benjamin and Andrade (2003) on investigating bursting capacity. A brief summary of critical parameters from existing bursting tests can be seen in Table 2, which contains principal dimensions, material type, introduced damage and failure location, etc. Figure 7(a) denotes a typical burst set-up of a pipe. An end cap is introduced in order to fashion a space for pressurisation in a pipe segment. A pressure meter is deployed to detect the bursting pressure, which is one of the critical factors in such a test. An alternative way to seal pipe segments is by using end flanges and flat rubber (Lancaster & Palmer 1996a), which can eliminate the welding effect. But it is only suitable for pipes with a small diameter.

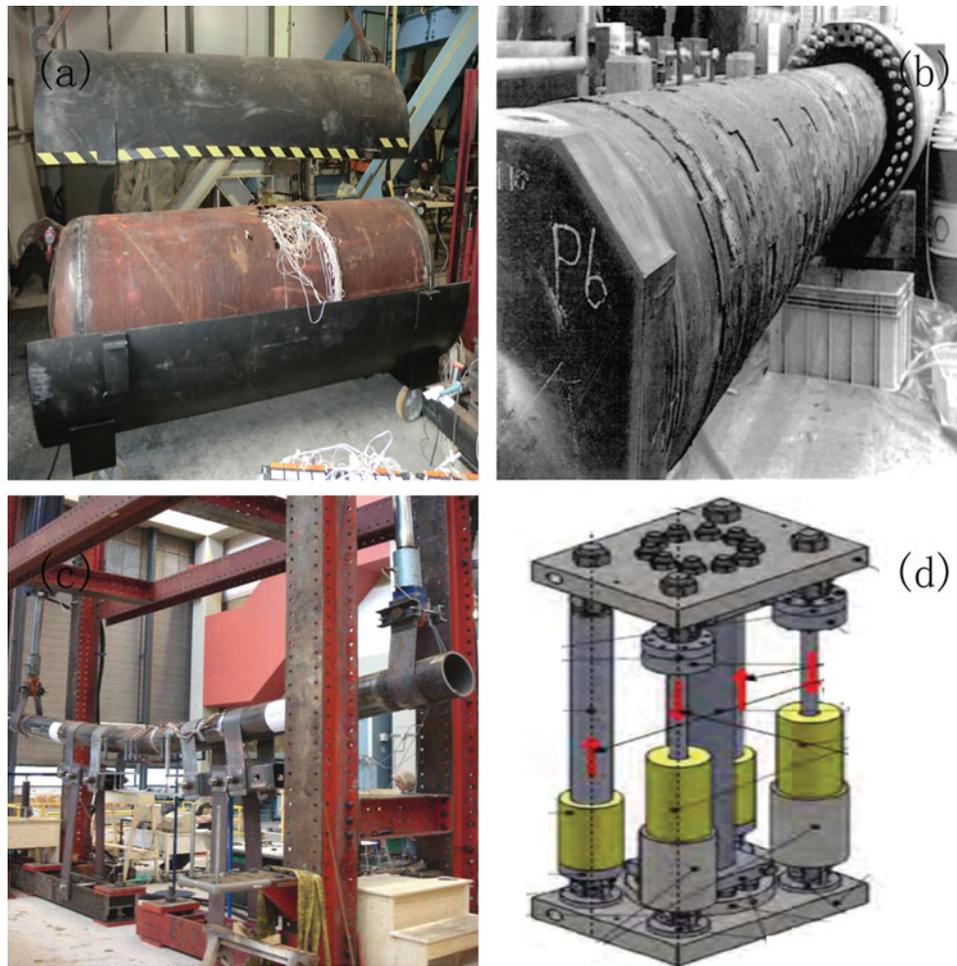


Figure 7. The typical test set-ups: (a) a set-up for bursting test (Ghaednia et al. 2015b); (b) a set-up for pipe under external pressure (Gresnigt et al. 2000); (c) a four-point bending test set-up (Hilberink 2011); (d) a set-up for pure bending test (Levold et al. 2013). (This figure is available in colour online.)

When it comes to the bursting capacity of damaged pipes, the test procedures and facilities are similar with intact pipe tests. The only difference is that damage should be carefully introduced in advance. Generally speaking, there are two ways to introduce damage under laboratory environments. One is that pipe damage is introduced in a situation without internal pressure, while the other is a situation involving internal pressure. As pointed out by Macdonald and Cosham (2005): ‘the most realistic tests are those in which the dent and gouge are introduced into pressurised pipe under dynamic conditions’. Therefore, the internal pressure situation can be used to mimic a realistic situation. One example is Ghaednia et al. (2015b), who carried out a denting test to produce a dent on pipe surface when keeping the internal pressure as constant (30% of the yielding internal pressure).

When introducing a metal loss on a pipe surface, a grinding process should be used to eliminate the effect of a possible existing crack (Lancaster & Palmer 1996a; Bjørnøy et al. 2000). This is because a crack is easily associated with other kinds of structural damage. Studies from Ghaednia et al. (2013, 2015a, 2015b) have investigated the effects of crack on pipe bursting capacity. Under laboratory environments, there are basically two ways to introduce a prescribed crack in pipe walls. One is the cyclic loading method, which can introduce a fatigue crack in a

region with prescribed metal loss and/or dent. Preliminary work has been conducted to clarify the required number of loading cycles for producing cracks, finding that approximately around 50,000 loading cycles on the region with metal loss (V-notch) could introduce a 0.3 mm (pipe thickness is 8.5 mm) depth crack at the tip of the notch (Silva et al. 2012; Ghaednia et al. 2015b). However, a disadvantage of this method is that it is not easy to pre-control the initiation place of crack and crack size. The other method is to use laser graving technique that can precisely control the size and location of a tiny crack on pipe walls. Besten (2015) successfully introduced 2D artificial edge cracks by laser to mimic the welding-induced defects.

4.2. External pressure test of pipe

Buckling-induced collapse can occur when pipelines are subject to external pressure. Considerable test research such as Dyau and Kyriakides (1993), Park and Kyriakides (1996), Gresnigt et al. (2000), Bruschi et al. (2005) and Netto et al. (2006) has been done on such collapse capacity of pipelines. A typical set-up for pipe external pressure test can be seen in Figure 7(b). In this example, the pressure vessel was a cylindrical pressure chamber made of high-strength steel with large pressurisation capacity. The testing specimen was sealed at the ends with solid plugs.

Table 3. A summary of critical parameters in existing external pressure tests.

S.N	Parameters	Domain
1	Outer diameter D (mm)	30–510
2	Wall thickness t (mm)	0.9–24
3	D/t	18–45
4	L/D	20–30
5	Materials	Steel,Al
6	Dent direction	Longitudinal
7	d_d/D (%)	0.4–1.6
8	Dent ovalisation δ (%)	0.04–24

Table 4. A summary of critical parameters in existing bending tests.

S.N	Parameters	Domain
1	Outer diameter D (mm)	168–559
2	Wall thickness t (mm)	6–24
3	D/t	20–45
4	L/D	9–24
5	Materials	Steel
6	δ_0 (%)	0.078–0.3
6	d_m/t (%)	30–50
7	prescribed internal pressure (MPa)	18–22
8	Failure location	Damaged region/section

A volume-controlled strategy was deployed based on a high-power pump for pressurisation. The pumping speed was quite slow to maintain a quasi-static loading procedure. A brief summary of critical parameters from existing collapse tests can be seen in Table 3, which contains principal dimensions, material types, introduced damage and failure locations, etc.

4.3. Bending test of pipe

The bending moment is one of the dominant load conditions on pipelines. Therefore, such test research can be seen in the literature like Gresnigt et al. (2001, 2009), Guarracino et al. (2009), Hilberink (2011), Vasilikis et al. (2015) and Es et al. (2016). A few tests (Vitali et al. 2005; Levold et al. 2013; Levold, Restelli et al. 2013) have even focused on the bending capacity with a combination of axial force and internal pressure. For these tests, the typical set-up to investigate the bending capacity is a four-point bending method, as illustrated in Figure 7(c). A brief summary of concerned parameters from existing bending tests can be seen in Table 4, which contains principal dimensions, material type, introduced damage and failure locations, etc.

As a classical test method, four-point bending has been widely deployed to investigate pipe subjected to bending moment. By applying two vertical loads on a pipe, a pure bending moment can be realised within the central part of specimen between two inner points (either loading points or support points). The side length of pipe during test is the bending arm, associated with the loading capacity, which determines the exerted bending moment on specimens.

There are several points that should be highlighted in a successful four-point bending test. First, the specimen length should be long enough in order to eliminate the end effect (both supports and loading points). For the central pipe segment under pure bending, the minimal length should be at least $4D$ (D is the pipe outer diameter) (Hilberink 2011; Kim et al. 2013; Mohd et al. 2014; Vasilikis et al. 2015; Es et al. 2016). For the

bending arm, a minimum length is determined by both the loading capacity and the bending capacity of specimens. In addition, extra length for loading heads and support bases is required from a practical perspective. Meanwhile, the maximum specimen length is of course restricted by both the lab conditions and the experiment budget. Overall, the whole specimen length for offshore pipe test is generally between $9D$ and $24D$, as seen in Table 4. The second point is the loading strategy. The vertical loads can either be exerted on the pipe end (Hilberink 2011) or on the middle span (Vitali et al. 2005) depending on the specific laboratory conditions. In order to avoid artificial pipe failure induced by a high concentration force, wide strips are generally adopted for loading heads, as some tests such as Gresnigt et al. (2001), Vasilikis et al. (2015) and Es et al. (2016) have practiced. Another point is the applied boundary conditions. The support bases should be carefully designed so that the pipe ovalisation cannot be strictly restricted. As the tests by Guarracino et al. (2009) have shown, ovalisation could cause a maximum discrepancy of 1.59 times between the longitudinal compression strain on the pipe's top location and the tensile strain in the bottom location. The structure should be reinforced if the unconcerned regions are prone to fail in advance. For instance, extra sleeves (Vitali et al. 2005) were used on side pipe segments to avoid artificial failure. Apart from the four-point bending set-up, some special customised facilities can be used for the bending test, as illustrated in Figure 7(d) (Levold et al. 2013; Levold, Restelli et al. 2013). This method saves a lot of laboratory space once the facility has been set-up.

In sum, common methods for introducing damage including dent, metal loss and crack under lab environments are concluded as follows:

- (1) When introducing a metal loss such as gouge and notch, a typical method is the electro-discharging method. With specified electrodes, metal loss with any shape and size could be introduced precisely. An alternative is to deploy a mechanical method. For instance, Lancaster and Palmer (1996a) produced a gouge with a high-speed milling. However, it should be noted that, based on this method, cracks should be strictly controlled. Otherwise, the crack could be easily introduced by the mechanical contact which will largely affect the accuracy of strength results. In order to avoid such effect, measurements such as grinding could be taken to exclude the shallow surface crack.
- (2) If a crack is going to be prescribed, careful processes and measurements should be carried out because of the instability feature of a crack. There are basically two ways to introduce a prescribed crack in pipe walls. One is the cyclic loading method, which can introduce a fatigue crack in a region with prescribed metal loss and/or dent. However, a disadvantage of this method is that it is not easy to pre-control the crack size and initiation place of crack. The other method is the laser graving technique, which can precisely control the size and location of a tiny crack on pipe walls.
- (3) In order to add a dent, specified indenters should be designed first. Different shapes of indenters, such as spherical shape, rectangle shape and wedge shape, can

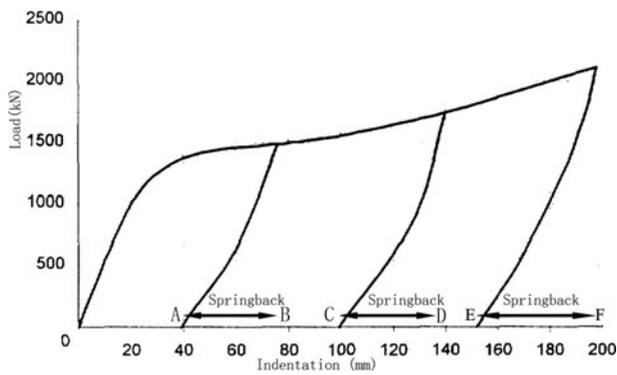


Figure 8. The relation of load and indentation displacement during indentation process (Bjørnøy et al. 2000) (the horizontal coordinate denotes the indentation displacement and the vertical coordinate denotes the indenting load).

be deployed. There are two ways to introduce a dent on pipe walls. One is the quasi-static way, in which an indenter is loaded with a very low speed in order to eliminate the dynamic effect. The other is the dynamic way, which requires a high-speed indenter to impact with specimens. The initial impact energy should be well introduced so that artificial cracks are not produced. Another aspect for introducing a dent is the spring-back phenomenon after loading. As seen in Figure 8, the displacement (AB , CD , EF) denotes the spring-back of each denting process. It should be subtracted from the whole denting displacement when conducting following research.

- (4) When introducing combined damage, special attention should be paid to the sequence of every single piece of damage, since the existing type and size of damage could be affected by new processes and damage. Delicate design is needed in order to avoid such adverse interaction. For instance, in order to produce a combined dent and metal loss, a special indenter has been designed (Bjørnøy et al. 2000; Ghaednia et al. 2015b) with a protruding tiny wedge that is coordinated with the existing V-notch. Thus, the combined dent and notch was then well produced.

5. Numerical method for strength evaluation

The numerical method is an alternative to experiments, especially when full-scale tests are not available. Numerical simulation provides reliable results compared with pipe test results

in terms of the shape of buckling modes and the relation between pipe bending moment and curvature. A brief summary from existing numerical research is shown in Table 5, which contains some specific information related to numerical models such as the principal dimensions, materials, load conditions, mesh, damage types and adopted software. This section summarises the numerical methods for pipe strength of damaged pipes. Specific details on how to introduce, simplify and simulate structural damage are presented. Influential parameters in FEA related to offshore pipelines such as mesh, material property and boundary condition are identified and discussed.

5.1. General requirements

Choosing a suitable software is a good start for numerical simulation on offshore pipes. Depending on the analysis types, the selected software should have a suitable solver that can account for nonlinear behaviours such as material nonlinearity, geometry nonlinearity or contact nonlinearity. To investigate the ultimate strength of pipeline structures, a static solver generally suffices. In case the dynamic effect should be accounted for – for instance, for pipes under dynamic loading conditions – explicit solver that does not require matrix iterations is much better than the implicit static solver in terms of obtaining a reasonable result. Relevant research on tubular structures adopting a dynamic explicit solver can be seen in Bisagni (2005). Newton–Raphson’s iterative criterion is generally deployed in numerical solution. Either the load-controlling method or the displacement-controlling method can be used. However, a disadvantage of the traditional Newton method is that the load-displacement path beyond a limit point cannot be well traced once the limit solution has been reached. In order to make up for such a limitation, Riks (1972, 1979) proposed the updated arc length method, which can easily capture the post failure/buckling behaviours of a structure. Common commercial software for nonlinear finite element analysis includes Abaqus (Abaqus6.13 2013), Marc (Yeh & Kyriakides 2015) and Ansys (Vaziri & Estekanchi 2006; Polenta et al. 2015).

When introducing structural damage on pipe surface, how to model the shape of each damage is a priority issue. Figure 9 shows the FEA model of three types of damage on pipes. Simplistically, sinusoidal shape (Prabu et al. 2010) is a good choice for the modelling of dent, as seen in Figure 9(a). Other shapes such as spherical shape (Cai et al. 2016) and elliptical shape (Blachut & Iflefel 2011) can be also deployed for modelling, although

Table 5. A summary of numerical models in existing numerical research.

S.N	D (mm)	D/t	Material	Damage	Load (dominant load)	Mesh	Software
(1) Levold et al. (2013)	168	26.5	X70	Metal loss	Combined bending, internal pressure and axial force (bending)	C3D8R (solid)	ABAQUS
(2) Park et al. (1996)	31.8	18–33	Stainless steel	Dent	External pressure	S4R (shell)	ABAQUS
(3) Vitali et al. (2005)	559	26.5, 34.2	X65	Intact	Combined bending, internal pressure and axial force (bending)	Shell	ABAQUS
(4) Bartolini et al. (2014)	813	39, 74	X65	Intact	Combined bending, and axial force	Solid	ABAQUS
(5) Lee et al. (2015)	168.3	9.5	X42	Metal loss	Internal pressure	Solid	ANSYS
(6) Vasilikis et al. (2015)	1068	65–120	X70, X60	Intact	Bending	S4R (shell)	ABAQUS

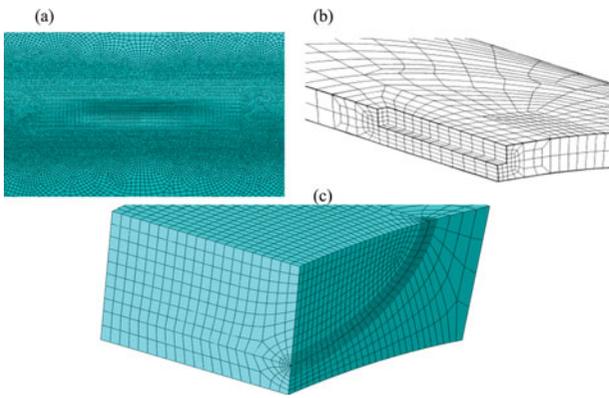


Figure 9. The numerical models of different types of structural damage on pipe surface. (a) dent (Cai et al. 2016); (b) metal loss (Blachut & Iflefel 2011); (c) surface crack. (This figure is available in colour online.)

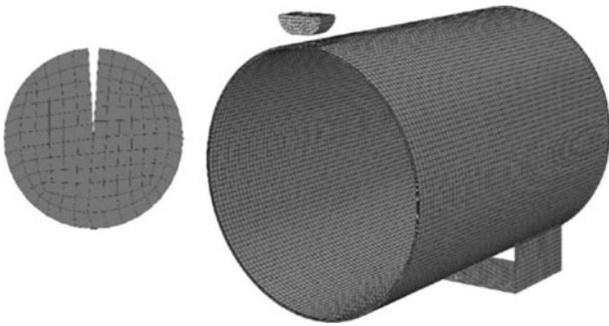


Figure 10. An example of numerical model of cracked pipe (Ghaednia et al. 2015b). (This figure is available in colour online.)

specific shape does not have significant effect on the residual strength of pipes as long as the depth and length of dent are the same. For a metal loss on pipe surface, it is usually simplified to a regular shape such as V-shape, rectangular shape (Blachut & Iflefel 2011) and semielliptical shape (Pluvinage 2006), as seen in Figure 9(b). For a surface crack on pipes, it is often modelled as a half elliptical shape with a refined mesh around its tips, as seen in Figure 9(c). Special strategy such as collapse element for cracked area should be deployed to capture the fracture characteristics.

5.2. Mesh

Mesh is a key factor during numerical research. It includes element type selection and mesh density selection.

The selection of element type strongly depends on the investigated problems. For intact pipes, for instances, the deployed element type is normally a shell element such as S4R and S8R in Abaqus (Abaqus6.13 2013), or Shell181 and Shell93 in Ansys (Fluent 2009). In contrast, for damaged pipes with a surface crack or metal loss, it is better to select solid elements such as C3D8R (an eight-node linear brick element), C3D10R (a ten-node quadratic tetrahedron element) or C3D20R in order to capture detailed structure behaviours and crack front features, as illustrated in Figure 10. Generally speaking, the solid element can provide a better prediction than a shell element, but it would be more time-consuming. The element integration rule, which affects the accuracy of output results, should be selected carefully. For instance, the reduced integration rule can not only reduce simulation time, but also avoid the self-locking effect

(Abaqus6.13 2013). However, it is prone to be affected by hourglass phenomenon, which largely reduces the accuracy of simulation. A practical technique to detect the severity of hourglass during simulation is to check the hourglass energy, which should be less than 5% of the system internal energy (DNV 2013b). Another aspect involved in the element type selection is the order of the element. A high-order element can provide a better stress and strain prediction, but causes more simulation time. However, it should be noted that a linear element such as S4R in Abaqus is normally more suitable than a high-order element such as S8R for analysing cases with large displacement and rotation.

For a pipe with dent or metal loss on its surface, the mesh density should be largely refined so that the artificial local bending stress and stress concentration will not be introduced. And the shape of dent or metal loss could be accurately modelled. A quantitative criterion for determining mesh size is to employ the critical half-wave length λ_{cl} , as seen in Equation (3), where R is the pipe radius and t is the pipe wall thickness. It is related to the buckling of cylindrical shell (Song et al. 2004; Prabu et al. 2010). The mesh size deployed in the interesting areas should be less than the critical half-wave length, for example, 3–6 elements within one half-wave length (DNV 2013b). An alternative approach to determine mesh density is to carry out a mesh sensitivity study. When reducing the mesh size to half scale, the structure response is less than 1%. Under this situation, the mesh density could therefore be considered good enough for numerical research:

$$\lambda_{cl} = 1.728\sqrt{Rt} \quad (3)$$

For a pipe with crack on its surface, the mesh should be carefully arranged. Crack characteristics such as tip singularity should be expressed through special mesh strategies. However, in the study of pipe ultimate strength accounting for crack singularity, more simulation time is required and numerical convergence is generally difficult. A practical method to realise crack tip singularity is called the collapse technique. Based on this method, all the side nodes of the crack tip elements collapse into a single node, as illustrated in Figure 11. Point A is the crack tip, while element E is the special collapsed element with six nodes. According to this method, it is formed by an eight-node quadrilateral shell element, as illustrated in Figure 11(c). In order to introduce a crack during numerical simulation, both a solid element and a shell element (Vaziri & Estekanchi 2006) can be used. This method is deployed in the research of Estekanchi and Vafai (1999) and Vaziri and Estekanchi (2006). Mesh density around the cracked tip is important and should be refined. It has been demonstrated that four layers (Estekanchi & Vafai 1999; Vaziri & Estekanchi 2006) of elements, as illustrated in Figure 11(a), at the crack tip region are capable of capturing the main crack characteristics. Recently, in order to circumvent the mesh dependence during a crack analysis, a new method called the extended finite element method (XFEM) (Abaqus6.13 2013) was proposed. This method can predict the crack initiation and propagation by modelling the crack as an enriched feature and has greatly reduced efforts to mesh crack singularity. To date, little numerical research has looked at the effect of specific crack dimensions on pipe residual ultimate strength. The relationship

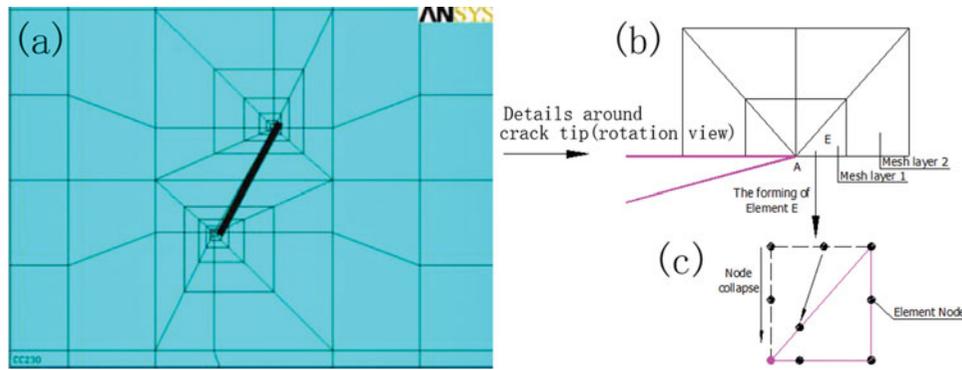


Figure 11. The mesh strategy accounting for crack tip singularity: (a) FE mesh (Vaziri & Estekanchi 2006); (b) mesh details; (c) element collapse method. (This figure is available in colour online.)

between fracture failure and strength is worthy of exploration in future research.

5.3. Material properties

The material property is another key factor during numerical research. Three typical material models – the linear elastic model, the elastic-perfectly plastic model and the elastic-plastic model – are deployed in numerical research. The application of the linear elastic model is limited since it only has a linear stress-strain relation. In engineering practice, the majority of materials behave in an elastic-plastic way. Therefore, the elastic-plastic model is generally deployed. Meanwhile, it can provide a conservative prediction, as shown in the numerical research of Paik (2007). However, the convergence problem is easily induced by using this model from a practice point of view. Hence, it is better to deploy the elastic-plastic model accounting for material hardening. In theory (Chakrabarty 2010), some critical criteria should be obeyed to describe the material plastic behaviours such as the yielding criteria, the material flow criteria and the hardening criteria. The common criteria used in a metallic pipe include the von Mises yield criterion, the isotropic hardening criterion and the Mises flow criterion.

Basic material properties including yield strength, ultimate tensile strength, the maximum elongation ratio and material curve can be obtained from material test, which is a classical approach to obtain exact data for numerical simulation. Alternatively, approximate empirical equations based on basic material inputs are usually deployed for material curve. A typical example is the formulation from Ramberg and Osgood (1943), as seen in Equation (4) with 0.002 plastic strain at yield point. Nevertheless, it is not accurate enough to denote the stress-strain relation after the occurrence of material necking. Due to the stress triaxiality in necking zone (Zhao et al. 2016), the engineering stress cannot be accurately calculated by the original cross-section of material samples. Accordingly, corrections are needed. For instance, Pakiding (2007) deployed a parabolic relation to express the relation of a metallic material. It should be noted that such correction is not always the same within different metallic materials due to different material producing workmanship. Based on the transformation of Equations (5) and (6), the true stress and strain can be then obtained, which are directly used for FEA:

$$\varepsilon_{\text{eng}} = \sigma_{\text{eng}}/E + 0.002(\sigma_{\text{eng}}/\sigma_y)^n \quad (4)$$

$$\sigma_{\text{true}} = \sigma_{\text{eng}}(1 + \varepsilon_{\text{eng}}) \quad (5)$$

$$\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{eng}}) \quad (6)$$

In spite of the common used isotropic feature in metallic pipes, anisotropy is sometimes very prominent due to different manufacturing methods. For instance, the UOE manufacturing method (Westergaard 1952; Gresnigt et al. 2000; Bruschi et al. 2005; Vitali et al. 2005) using for production of longitudinal welded large diameter pipes induces ‘the Bauschinger effect’, which decreases the yield strength of material during compression. Therefore, pipe’s ultimate strength could be reduced. As Bruschi et al. (2005) pointed out: ‘the bending capacity of pipelines could be reduced by 16% when the compression yield stress of material in the hoop direction reduced to 85% of the longitudinal yield stress during simulation’. For seamless pipe that producing without a seam or weld, the anisotropy is not as obvious as the former one. Under this circumstance, the Hill48 yielding criterion (Hill 1948) is generally deployed to account for such anisotropy characteristic in numerical research. For pipes with structural damage, such anisotropy should be carefully taken into account depending on both pipe types and causes of damage such as a high-speed impact by a foreign object.

5.4. Boundary conditions

Boundary conditions largely affect the accuracy of numerical research. A basic criterion for selecting boundary conditions in numerical simulations is that any simplification or idealisation should conform to the real situations. Therefore, a trade-off between calculation accuracy and calculation time must be accounted for.

For metallic pipes subjected to internal or external pressure, extra pipe segments are often introduced to make sure that the boundary is far enough from the concerned pipe segments. With this regard, the effect of boundary condition will be neglected. And a fixed boundary condition can be simply deployed at both pipe ends. When the studied pipes have no structural damage, symmetric boundary condition such as half model or

one-quarter of the model can be introduced. However, such boundary conditions should be carefully deployed for damaged pipes. It is because that the failure patterns may be affected as well.

When the pipes are subjected to pure bending moment, whether or not constrain the ovalisation of pipe ends is a critical point. The reason is that such boundaries affect the stress distributions and failure modes of pipes. There are two ways to set a free ovalisation boundary at the pipe ends in numerical simulations. One is by introducing an extra sliding plane near the pipe end. By forcing the pipe ends to contact with the sliding plane, a local boundary restriction is formed and, therefore, the radial motion is set to free (Guarracino et al. 2009). However, because of the contact analysis, the entire model calculation time increases greatly. A simple alternative is to use a kinematic coupling constraint for all the nodes at pipe end, which can easily release the radial motion. The calculation time is largely saved with a good accuracy. In case it is difficult to define boundary conditions, a sensitivity study could be carried out so that the insignificant degrees of freedom can be excluded and a suitable boundary condition will be then selected.

5.5. Others

Other parameters such as the initial imperfection, the modelling strategy and the loading method will affect the numerical research. The initial imperfection is generally introduced during the pipe manufacturing process, which typically has an oval or lobed shape (Bartolini et al. 2014). The effect of initial imperfection largely depends on the exertion of dominant loads on pipes. For instance, the effect is insignificant for pipes subjected to pure bending because the disturbances of loading and asymmetrical deformation are large enough to cause structure failure. In contrast, for pipes under uniaxial force, the initial imperfection could reduce pipe buckling strength by as much as 50% (Song et al. 2004). In numerical simulation, there are basically two ways to introduce initial imperfections. One is to deploy a single or a combined structure eigenvalue modes and the other is to deploy the measurement data from tests. The modelling strategy can also affect the numerical research. Not every single detail of structure geometry should be accounted for as long as the major concerned part has been included. Therefore, both accuracy and simulation time would be reasonable. The loading method also has significant effect on pipe simulation. A common way to add loads is to exert force on a multiple point constraint or coupling point that can reduce the risk of introducing artificial structure failure (Abaqus6.13 2013).

6. Analytical method for strength evaluation

The classical theory has built a solid foundation for structure ultimate strength within elastic domain. However, it generally overestimates the capacity of metallic pipes. For instance, the buckling strength of thin-walled pipes under uniaxial compression is considerably smaller than theoretical predictions (Timoshenko & Gere 2009). Accordingly, researchers developed

a number of empirical or semi-empirical equations for supplement of strength predictions based on existing theory, experiments and numerical simulations. In this section, some analytical solutions for ultimate strength of both intact and damaged metallic pipes are summarised and discussed. Meanwhile, simple derivation of a few of these equations is performed in order to give a better understanding on the mechanism of pipe strength.

6.1. Prediction of strength under external pressure

When pipes are subjected to external pressure, buckling failure is the dominant failure pattern. Equation (7) denotes the analytical solution of the elastic buckling pressure (P_{ee}) subjected to external pressure based on classical theory (Timoshenko & Gere 2009). Additionally, Equation (8) can be used to predict the critical pressure (P_{ye}) of a perfect pipe shell at the yielding point based on the equilibrium relations:

$$P_{ee} = \frac{2E}{(1 - \nu^2)} \left(\frac{t}{D} \right)^3 \quad (7)$$

$$P_{ye} = \frac{2\sigma_y t}{D} \quad (8)$$

The collapse capacity of a pipe mainly depends on the initial imperfections of metallic pipes. The initial ovalisation (δ_0) is one of the typical imperfection forms that deployed for analytical solutions. Timoshenko and Gere (2009) proposed a linear relationship (as seen in Equation (9)) to predict the buckling capacity of pipes (P_{ce}). Both elastic buckling pressure (P_{ee}) and yielding pressure (P_{ye}) were integrated together. A modification of Equation (9) was deployed by BS8010 (1993) and DNV (2013a), as seen in Equation (10). As demonstrated by the test research of Gresnigt et al. (2000), it can provide a better prediction to the collapse pressure of metallic pipes.

$$(P_{ce} - P_{ee})(P_{ce} - P_{ye}) = P_{ce}P_{ee} \left(\frac{3\delta_0 D}{t} \right) \quad (9)$$

$$(P_{ce} - P_{ee})(P_{ce}^2 - P_{ye}^2) = P_{ce}P_{ee}P_{ye} \left(\frac{2\delta_0 D}{t} \right) \quad (10)$$

For a pipe with metal loss, Equation (11) is deployed by Bai et al. (1998, 1999) to predict the collapse pressure. It should be noted that only the depth of metal loss (d_m) was accounted for in this equation, where R is the average pipe radius, P_{ee} is the elastic buckling pressure calculated from Equation (7), h is the pipe wall thickness subtracting the depth of metal loss d_m , δ_{\max} is the maximum ovalisation of pipe cross-section:

$$(P_{ce})^2 - \left(\frac{\sigma_y h}{R} + \left(1 + \frac{6\delta_{\max}}{h} \right) P_{ee} \right) P_{ce} + \frac{\sigma_y h}{R} P_{ee} = 0 \quad (11)$$

6.2. Prediction of bursting capacity

Bursting capacity is a critical feature of metallic pipes subjected to internal pressure. Equations (12) and (13) denote the analytical solutions of hoop membrane stress (σ_θ) and longitudinal stress (σ_l) when pipes are subjected to internal pressure. They demonstrate that the failure of an intact pipe initiates in its longitudinal direction. Therefore, the ultimate strength of pipe subjected to internal pressure can be also expressed as Equation (8):

$$\sigma_{\theta} = \frac{p_i D}{2t} \quad (12)$$

$$\sigma_l = \frac{p_i D}{4t} \quad (13)$$

For the dented metallic pipe, Orynyak et al. (1999) developed a simple analytical equation to predict the bursting strength with respect to dimensionless length of dent ($\lambda = l_d/\sqrt{Rt}$). However, only a single dimension of dent was taken into account. And the dent is assumed to be infinite in pipe longitudinal direction. The equation is shown as follows:

$$p_b = \frac{\sigma_u t}{R} \left(\sqrt{\lambda^4 + 1} - \lambda^2 \right) \quad (14)$$

For the metallic pipe with metal loss, there are considerable empirical equations to denote its bursting capacity. Kiefner et al. (1973) and Lancaster and Palmer (1996a) deployed Equation (15) to calculate the bursting capacity of pipes. In this equation, the metal loss depth (d_m) and axial length (l_m) are taken into account. $\bar{\sigma}$ is the flow stress of the material that generally lies between the material yield strength and the ultimate tensile strength; M_f is the bulging parameter relating to axial length (l_m) of metal loss. Nowadays, Equation (16) is another widely deployed expression by DNV (2004), BSI (2005) and Bogdan et al. (2009), etc., for bursting capacity of damaged pipes, where Q is the correction factor based on the length of metal loss in pipe longitudinal direction, which can be expressed as $Q = \sqrt{1 + 0.31 \left(\frac{l_m}{\sqrt{Dt}} \right)^2}$.

$$\sigma_{cb} = \bar{\sigma} \frac{1 - d_m/t}{1 - d_m/(M_f t)} \quad (15)$$

$$P_b = \frac{2t}{(D-t)} \sigma_u \frac{1 - d_m/t}{1 - d_m/(tQ)} \quad (16)$$

6.3. Prediction of bending capacity

When pipes are subjected to bending moment, the failure patterns could be elastic collapse, elastic-plastic failure or fracture failure. For a metallic pipe with high D/t ratio, the dominant failure pattern is elastic collapse. Structures will generally fail in a sudden. While for a pipe with smaller D/t ratio (normally less than 100 but larger than 35), the dominant failure pattern is elastic-plastic failure in the form of buckles on pipe compression side. Structures can continue to carry load after the ultimate strength has reached. No sudden collapse happens. Providing the bending stress in the entire pipe cross-section is uniform, the analytical solution of ultimate bending moment is first derived when pipes are subjected to a combination of bending and axial force.

Figure (12) is the sketch of stress distribution of pipe cross-section at the limit condition, assuming that the material is elastic-perfectly plastic model. Pipe reaches the ultimate condition when the entire pipe cross-section has reached the yield strength of material (σ_y). First of all, we need to obtain the location of plastic neutral axis AB , as shown in Figure (12).

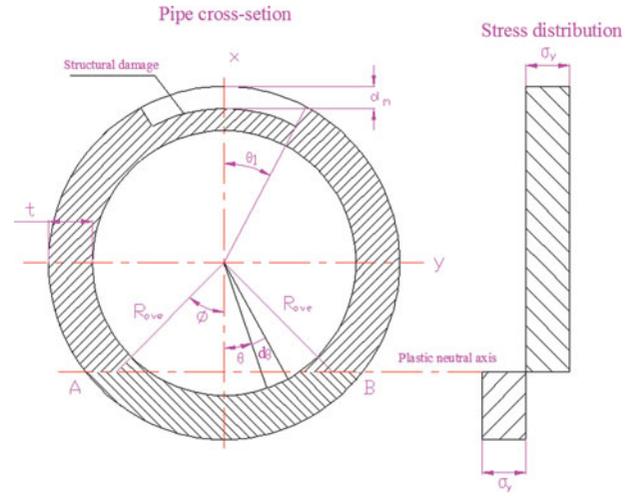


Figure 12. The sketch of stress distribution on a pipe cross-section. (This figure is available in colour online.)

Integrating all the stress on the pipe cross-section, the axial force F can be expressed as:

$$\begin{aligned} F &= 2 \int_0^{\phi} -\sigma_y t R d\theta + 2 \int_{\phi}^{\pi-\phi} \sigma_y t R d\theta \\ &= 2Rt\sigma_y(\pi - 2\phi) \end{aligned} \quad (17)$$

where ϕ is the plastic neutral axis angle. Hence, it can be denoted as

$$\phi = \frac{F - 2\pi Rt\sigma_y}{4Rt(\sigma_y)} \quad (18)$$

The force arm y_{comp} and y_{tens} can be expressed as

$$\begin{aligned} y_{\text{comp}} &= \frac{R^2 t \int_0^{\phi} \cos \theta d\theta}{Rt\phi} = R \frac{\sin \phi}{\phi} \\ y_{\text{tens}} &= R \frac{\sin \phi}{\pi - \phi} \end{aligned} \quad (19)$$

Hence, the ultimate bending moment can be expressed as

$$\begin{aligned} M_c &= 2 \int_0^{\phi} -\sigma_y t R^2 \cos \theta d\theta + 2 \int_{\phi}^{\pi-\phi} \sigma_y t R^2 \cos \theta d\theta \\ &= 4R^2 t \sigma_y \sin \phi \end{aligned} \quad (20)$$

It should be noted that Equation (20) is only strictly derived under the assumption of elastic-plastic material model, although it can normally provide a conservative prediction for material with hardening effect in engineering practice. When there is no axial force, that is to say, $\phi = \pi/2$. Hence, the ultimate bending moment is expressed as Equation (21), which is also called as plastic bending moment:

$$M_y = 4R^2 t \sigma_y \quad (21)$$

If hardening effect is taken into account, the bending capacity of metallic pipe under pure bending can be expressed as

Equation (22) (for detail derivation, please refer to Westergaard (1952) and Bai and Bai (2014a)):

$$M_{yh} = 4R^2 t \sigma_y + R^2 t \pi (\sigma_u - \sigma_y) \quad (22)$$

Therefore, the analytical solution of bending capacity of metallic pipes is simply derived. However, the influential factors such as initial imperfection, residual stress and material hardening have not been accounted for. Hence, empirical equation such as Equation (23) is generally deployed to express the ultimate bending moment of pipes taking into account all these effects in engineering practice:

$$M_c = M_y \left(c_1 - c_2 \frac{D}{t} \right) \quad (23)$$

where M_y is the plastic bending moment of pipe, as seen in Equation (21), c_1 and c_2 are correction coefficients that were proposed through tests. Such coefficients varied a little bit within different research. For instance, c_1 and c_2 are 1.05 and 0.0015, respectively, from the research of Bai and Bai (2014b). But in BS8010 (1993), the adopted values are 1 and 0.0024, respectively. Additionally, the critical deformation of pipes in terms of pipe strain (ε_c) can be deployed for pipe limit condition prediction since such structures have further load-carrying capacity after ultimate strength as mentioned before, as expressed in Equation (24) (Murphey & Langner 1985).

For a metallic pipe with very large D/t , the dominant failure patterns will be elastic buckling. Sudden collapse generally happens. The elastic buckling stress under pure bending is expressed as Equation (25) based on classical stability theory (Timoshenko & Gere 2009):

$$\varepsilon_c = 0.5 \left(\frac{t}{D-t} \right) \quad (24)$$

$$\sigma_{cbe} = \frac{Et}{R\sqrt{3(1-\nu^2)}} \quad (25)$$

When metal loss is introduced on pipe surface, a typical approach is to remove the corresponding area of metal loss. As seen in Figure 12, θ_1 is the half angle of metal loss in hoop direction, d_m is the depth of metal loss. Hence, the plastic neutral axis angle ϕ can be expressed as Equation (26). And the residual ultimate bending moment is changed to Equation (27). It should be noted that an assumption of infinite metal loss in pipe longitudinal direction is set in this derivation. The so-called 'neighbor response' (Zheng et al. 2005) induced by finite dimension such as length of metal loss (l_m) in longitudinal direction has not accounted for in this equation. Therefore, an effective thickness $f(l_m/\sqrt{Rt})t$ (Bai et al. 1998) was generally deployed to correct such length effect:

$$\phi = \frac{F - 2\pi Rt \sigma_y - 2Rd_m \sigma_y}{4Rt(\sigma_y)} \quad (26)$$

$$M_{ym} = 4R^2 t \sigma_y \sin \phi - 2R^2 d_m \sigma_y \sin \theta_1 \quad (27)$$

When there is a dent on the pipe surface, the effect of dent should be removed from the ultimate strength (M_c) of intact

metallic pipe. The influential term can be simply expressed as $F(\eta_c \beta)$, where β is the dent angle on pipe surface, and η_c is a correction factor based on dent locations and safety class, etc. The specific expressions are not listed here. For details, please refer to Bai and Bai (2014b). For the cracked pipe, fracture failure could occur when the crack is on the tensile side of pipes. With the stable growth of crack on metallic pipe, 'leak-before break' phenomenon (Pluvinage 2006) may happen. Detail equations will not be presented in this paper for the sake of clarity.

6.4. Prediction of strength under uniaxial loading

For metallic pipes subjected to uniaxial compression, elastic buckling may happen. The critical buckling stress can be also expressed as Equation (25) (Timoshenko & Gere 2009), which is the same with pipes subjected to pure bending moment. With the decrease of pipe D/t ratio, elastic-plastic failure occurs. Structure will not fail in a sudden any more. Instead, it can continue to carry load after plastic yielding. The plastic axial force is expressed as

$$T_{ya} = \pi D \sigma_y \quad (28)$$

When pipes are subjected to pure tensile load, the pipe wall will become thinning until the material yielding has reached. The maximum axial force can be also calculated by Equation (28). For the damaged pipes, no specific research on the analytical solutions was found, although a considerable amount of numerical research has focused on this subject.

6.5. Prediction of strength under combined loading

When metallic pipes are subjected to combined loading, interactive behaviours between each force (or corresponding stress) normally exist. For instance, Bai et al. (1994) proposed a bending moment (M) - tension (T) interaction relation as expressed in Equation (29) based on a numerical study, which is applicable for pipe D/t between 10 and 40:

$$\left(\frac{M}{M_c} \right)^2 + \left(\frac{T}{T_c} \right)^{2.4} = 1.0 \quad (29)$$

where M_c and T_c are the ultimate bending moment and ultimate tension force subjected to respective load.

For metallic pipes subjected to combined loading including axial force, bending moment, internal and external pressure, Equation (30) is deployed for design purpose based on the load-controlled condition (DNV 2013a). The exerted forces (M , T) should satisfy this criterion at all the pipe cross-sections, which is applicable for D/t between 15 and 45, where a_1 , a_2 and a_3 are correction parameters according to numerical simulations and tests, M_y , T_{ya} and P_b are the plastic bending moment, plastic axial force and bursting pressure of pipes under respective load. p_i and p_e are the internal pressure and the external pressure, respectively:

$$\left\{ a_1 \frac{M}{M_y} + \left\{ a_2 \frac{T}{T_{ya}} \right\}^2 \right\}^2 + \left\{ a_3 \frac{p_i - p_e}{P_b} \right\}^2 \leq 1 \quad (30)$$

A similar equation in terms of pipe longitudinal and hoop stress is deployed by Bai and Bai (2014a) to denote the strength of metallic pipes subjected to combined loading.

$$\left(\frac{\sigma_l}{\sigma_{\text{long}}}\right)^2 + \left(\frac{\sigma_\theta}{\sigma_h}\right)^2 - 2a_4 \frac{\sigma_l \sigma_\theta}{\sigma_{\text{long}} \sigma_h} = 1.0 \quad (31)$$

where σ_{long} and σ_h are the ultimate stress of metallic pipe in their respective directions, a_4 is correction factor depending on specific conditions such as compression or tensile.

For metallic pipes with structural damage, the former relations still satisfy. But it should be noted that the interactions between each damage type need to be accounted for, especially for the cracks on pipe. And the fracture failure is a critical point for metallic pipes. Research is needed to be done in this area.

7. Conclusion remarks

This paper has covered research on the residual ultimate strength of offshore metallic pipelines based on a literature review. It has revealed that such research is still within the engineering interest, especially when the pipes suffering from structural damage. The investigated pipe diameter-to-thickness ratios (D/t) majorly lie between 20 and 50. Influential parameters in terms of pipe load, installation process and material that affect the ultimate strength of pipes are categorised. Structural damage including dent, metal loss and crack is identified in this paper. Critical factors of damage such as dent length and crack depth are summarised. Furthermore, research and prediction methods on pipe residual ultimate strength in terms of experimental tests, numerical simulations and analytical predictions are summarised and discussed. Specific details on how to introduce, simplify and simulate structural damage are presented and discussed.

Based on current research, further studies are needed to be done, as summarized as follows.

- Fracture failure is a critical pattern of offshore metallic pipelines. The interactions between fracture failure and residual ultimate strength are still needed to be quantitatively investigated. Fracture mechanism should be taken into account during the research of residual ultimate strength on metallic pipes.
- Analytical research on metallic offshore pipelines with dent is rare, especially for the pipes subjected to pure bending moment. Specific influential parameters such as dent depth, angle, shape and length should be taken into account. Numerical simulations and experiments are needed to validate the proposed analytical solutions.
- For metal loss on the pipe surface, its length in the pipe longitudinal direction is generally ignored. Numerical simulations or experiments are needed to take into account such effect and hence to validate the proposed analytical predictions.
- Although a considerable amount of numerical research has focused on the dented metallic pipes subjected to uniaxial force, few analytical research is carried out. Further research is needed to develop analytical equations for dented pipes.

- For residual ultimate strength research of metallic pipelines, the investigations on damaged pipes subjected to dynamic loads and their relevant structure behaviours are rare. Impact effect from mechanical interference such as the residual stress and the variation of material properties has not been accounted for in the vast majority of research. The ultimate strength may be significantly affected due to such factors.

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References

- Abaqus613. 2013. Abaqus: User's manual, 6.13. Available from: <http://129.97.46.200:2080/v6.13/>.
- Abeele F, Galvan B, Ramos P, Muylle J. 2013. Numerical simulation of the interference between trawl gear and offshore pipelines. In: Proceedings of the Sixth International Pipeline Technology Conference. Ostend: Lab.Soete and Tiratsoo Technical.
- [ABS] American Bureau of Shipping. 2001. Subsea pipeline systems and risers. American Bureau of Shipping.
- Alexander C, Kiefner J. 1997. Effects of smooth and rock dents on liquid petroleum pipelines. In: 1999 API Pipeline Conference. Dallas (TX).
- Anderson TL, Anderson T. 2005. Fracture mechanics: fundamentals and applications. CRC Press LLC.
- ANSI. 1991. Manual for determining the remaining strength of corroded pipelines: a supplement to asme b31 code for pressure piping. New York (NY): American Society of Mechanical Engineers.
- API579. 2007. Fitness for service. Washington (DC): American Petroleum Institute.
- Bai Q, Bai Y. 2014a. Subsea pipeline design, analysis, and installation. Gulf Professional Publishing.
- Bai Y, Bai Q. 2014b. Subsea pipeline integrity and risk management. Gulf Professional Publishing.
- Bai Y, Hauch S. 1998. Analytical collapse capacity of corroded pipes. In: Proceedings of the Eighth International Offshore and Polar Engineering Conference. Montreal: International Society of Offshore and Polar Engineers.
- Bai Y, Hauch S, Jensen J. 1999. Local buckling and plastic collapse of corroded pipes with yield anisotropy. In: Proceedings of the Ninth International Offshore and Polar Engineering Conference. Brest: International Society of Offshore and Polar Engineers.
- Bai Y, Iglund RT, Moan T. 1994. Ultimate limit states of pipes under tension and bending. *Int J Offshore Polar Eng.* 4:313–319.
- Bartolini LM, Battistini A, Marchionni L, Parrella A, Spinazzè M, Vitali L. 2014. Pipe strength and deformation capacity: a novel FE tool for the numerical lab. In: Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering. San Francisco (CA): American Society of Mechanical Engineers; p. V06BT04A058–V06BT04A058.

- Barut A, Madenci E, Britt V, Starnes J. 1997. Buckling of a thin, tension-loaded, composite plate with an inclined crack. *Eng Fract Mech.* 58:233–248.
- Batte A, Fu B, Kirkwood M, Vu D. 1997. New methods for determining the remaining strength of corroded pipelines. In: *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*. Yokohama: American Society of Mechanical Engineers; p. 221–228.
- Beller M, Mattheck C, Zimmermann J. 1991. Stress concentrations in pipelines due to the presence of dents. In: *Proceedings of the First International Offshore and Polar Engineering Conference*. Edinburgh: International Society of Offshore and Polar Engineers; p. 421–424.
- Benjamin A, Andrade E. 2003. Predicting the failure pressure of pipelines containing nonuniform depth corrosion defects using the finite element method. In: *22nd International Conference on Offshore Mechanics and Arctic Engineering*. Cancun: American Society of Mechanical Engineers; p. 557–564.
- Besten J. 2015. Fatigue resistance of welded joints in aluminum high-speed craft: A total stress concept [dissertation]. Delft: Delft University of Technology.
- Bisagni C. 2005. Dynamic buckling of fiber composite shells under impulsive axial compression. *Thin-Walled Struct.* 43:499–514.
- Bjørnøy O, Rengård O, Fredheim S, Bruce P. 2000. Residual strength of dented pipelines, DNV test results. In: *Proceedings of the Tenth International Offshore and Polar Engineering Conference*. Seattle (WA): International Society of Offshore and Polar Engineers; p. 182–188.
- Blachut J, Iflefel I. 2011. Analysis of pipes containing plain and gouged dents. *Strain.* 47:e34–e51.
- Bogdan A, Likhman I, Ageev SM, Orynyak I. 2009. The limit load calculations for pipelines with axial complex-shaped defects. *Strength Mat.* 41:45–51.
- BP. 2012. BP energy outlook 2030. BP Statistical Review. Available from: <https://www.bp.com>
- Bruschi R, Bartolini L, Spinazzè M, Torselletti E, Vitali L. 2005. A numerical lab to predict the strength capacity of offshore pipelines. In: *Proceedings of the 24th International Conference on Offshore Mechanics and Arctic Engineering*. Halkidiki: American Society of Mechanical Engineers; p. 597–607.
- Bruschi R, Curti G, Dumitrescu A, Vitali L, Leira B. 1994. Strength criteria for hot pipelines susceptible to euler-bar buckling. In: *Proceedings of the Fourth International Offshore and Polar Engineering Conference*. Osaka: International Society of Offshore and Polar Engineers; p. 135–148.
- BS8010. 1993. Code of practice for pipelines, part 3: pipelines subsea: design, construction and installation. London: British Standards Institution.
- BSI. 2005. BS7910: guide to methods for assessing the acceptability of flaws in metallic structures. London: British Standards Institution.
- Cai J, Jiang X, Lodewijks G. 2016. Residual strength of metallic pipelines subjected to combined loads accounting for impact induced damage. In: *Proceedings of the 26th International Offshore and Polar Engineering Conference*. St. John's: International Society of Offshore and Polar Engineers.
- Carr M, Bruton D, Leslie D. 2003. Lateral buckling and pipeline walking, a challenge for hot pipelines. In: *Proceedings of the Offshore Pipeline Technology Conference*. Amsterdam: OPT; p. 1–36.
- Chakrabarty J. 2010. *Applied plasticity*. Vol. 88. New York (NY): Springer.
- Chen Y, Zhang H, Zhang J, Li X, Zhou J. 2015. Failure analysis of high strength pipeline with single and multiple corrosions. *Mater. Des.* 67:552–557.
- Cheng Y. 2013. *Stress corrosion cracking of pipelines*. Hoboken (NJ): Wiley.
- Cosham A, Hopkins P. 2004. The effect of dents in pipelines—guidance in the pipeline defect assessment manual. *Int J Pres Ves Pip.* 81: 127–139.
- CSA. 2011. *Oil and gas pipeline systems*. Mississauga: Canadian Standards Association.
- DNV. 2004. DNV-RP-F101 corroded pipelines. Norway: Det Norske Veritas.
- DNV. 2007. DNV-RP-F110, global buckling of submarine pipelines—structural design to high temperature/high pressure. Norway: Det Norske Veritas.
- DNV. 2010. DNV-RP-F111 interference between trawl gear and pipelines. Norway: Det Norske Veritas.
- DNV. 2013a. DNV-OS-F101 submarine pipeline systems. Norway: Det Norske Veritas.
- DNV. 2013b. DNV-RP-C208: Determination of structural capacity by non-linear FE analysis methods. Norway: Det Norske Veritas.
- Dyau J, Kyriakides S. 1993. On the localization of collapse in cylindrical shells under external pressure. *Int J Solids Struct.* 30:463–482.
- EIA. 2010. *Annual energy outlook*. Washington (DC): Energy Information Administration. Report no. 92010(9).
- El Naschie M. 1974. A branching solution for the local buckling of a circumferentially cracked cylindrical shell. *Int J Mech Sci.* 16:689–697.
- Es S, Gresnigt A, Vasilikis D, Karamanos S. 2016. Ultimate bending capacity of spiral-welded steel tubes—part i: experiments. *Thin-Walled Struct.* 102:286–304.
- Estekanchi H, Vafai A. 1999. On the buckling of cylindrical shells with through cracks under axial load. *Thin-Walled Struct.* 35:255–274.
- Fassina P, Bolzoni F, Fumagalli G, Lazzari L, Vergani L, Sciuccati A. 2012. Influence of hydrogen and low temperature on mechanical behaviour of two pipeline steels. *Eng Fract Mech.* 81:43–55.
- Fluent. 2009. *Fluent and Ansys User's guide 12.0*. Available from: <http://www.ansys.com/Products/Fluids/ANSYS-Fluent>
- Fowler J, Alexander C, Kovach P, Connelly L. 1994. *Cyclic pressure fatigue life of pipelines with plain dents, dents with gouges, and dents with welds*. Arlington (VA): American Gas Association, Inc.; Houston (TX): Stress Engineering Services, Inc., (United States). Report no. AGA-94015627.
- Fu B, Kirkwood M. 1995. Predicting failure pressure of internally corroded linepipe using the finite element method. New York (NY): American Society of Mechanical Engineers. Report no. conf-950695.
- Fyrileiv O, Aamlid O, Venås A, Collberg L. 2013. Deepwater pipelines—status, challenges and future trends. *Proc Inst Mech Eng M.* 227:381–395.
- Fyrileiv O, Collberg L. 2005. Influence of pressure in pipeline design: effective axial force. In: *Proceedings of the 24th International Conference on Offshore Mechanics and Arctic Engineering*. Halkidiki: American Society of Mechanical Engineers; p. 629–636.
- Galgoul N, Massa A, Claro C. 2004. A discussion on how internal pressure is treated in offshore pipeline design. In: *Proceedings of the International Pipeline Conference*. Alberta: American Society of Mechanical Engineers; p. 1887–1890.
- Ghaednia H, Das S, Wang R, Kania R. 2015a. Effect of operating pressure and dent depth on burst strength of NPS30 linepipe with dent-crack defect. *J Offshore Mech Arct Eng.* 137.
- Ghaednia H, Das S, Wang R, Kania R. 2015b. Safe burst strength of a pipeline with dent-crack defect: effect of crack depth and operating pressure. *Eng Fail Anal.* 55:288–299.
- Ghaednia H, Silva J, Kenno S, Das S, Wang R, Kania R. 2013. Pressure tests on 30-in. diameter X65 grade pipes with dent-crack defects. *J Pipeline Eng.* 12:61–67.
- Gong S, Ni X, Bao S, Bai Y. 2013. Asymmetric collapse of offshore pipelines under external pressure. *Ships Offshore Struct.* 8:176–188.
- Gresnigt A, Karamanos S, Andreadakis K. 2007. Lateral loading of internally pressurized steel pipes. *J Press Vessel Technol.* 129:630–638.
- Gresnigt A, Karamanos S. 2009. Local buckling strength and deformation capacity of pipes. In: *Proceedings of the Nineteenth International Offshore and Polar Engineering Conference*. Osaka: International Society of Offshore and Polar Engineers; p. 212–224.
- Gresnigt A, Van Foeken R, Chen S. 2000. Collapse of UOE manufactured steel pipes. In: *Proceedings of the Tenth International Offshore and Polar Engineering Conference*. Seattle (WA): International Society of Offshore and Polar Engineers.
- Gresnigt A, Van Foeken R. 2001. Local buckling of UOE and seamless steel pipes. In: *Proceedings of the Eleventh International Offshore and Polar Engineering Conference*. Stavanger: International Society of Offshore and Polar Engineers; p. 131–142.
- Guarracino F, Walker A, Giordano A. 2009. Effects of boundary conditions on testing of pipes and finite element modelling. *Int J Pres Ves Pip.* 86:196–206.

- Guo B, Song S, Ghaleb A. 2013. Offshore pipelines: design, installation, and maintenance. Gulf Professional Publishing.
- Hilberink A. 2011. Mechanical behaviour of lined pipe [dissertation]. Delft: Delft University of Technology.
- Hill R. 1948. A theory of the yielding and plastic flow of anisotropic metals. *Proc R Soc.* 193.
- Hopkins P, Corder I, Corbin P. 1992. The resistance of gas transmission pipelines to mechanical damage. In: *Proceedings of the International Conference on Pipeline Reliability*; Vol. 2. Calgary: CANMET.
- Hopkins P, Jones D, Clyne A. 1989. The significance of dents and defects in transmission pipelines. In: *Proceedings of the International Conference on Pipework Engineering and Operations*. London: IMechE. p. 137–145.
- Jin W, Shao J. 2004. Pressure test method of safety assessment on existed submarine pipeline. In: *Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering*. Vancouver: American Society of Mechanical Engineers; p. 275–280.
- Kiefner J, Maxey W, Eiber R, Duffy A. 1973. Failure stress levels of flaws in pressurized cylinders. In: *Proceedings of the Progress in flaw growth and fracture toughness testing*. ASTM International.
- Kim D, Mohd MH, Lee B, Kim D, Seo J, Kim B, Paik J. 2013. Investigation on the burst strength capacity of aging subsea gas pipeline. In: *Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering*. Nantes: American Society of Mechanical Engineers; p. V04AT04A027–V04AT04A027.
- Kim W, Kim Y, Kho Y, Choi J. 2002. Full scale burst test and finite element analysis on corroded gas pipeline. In: *Proceedings of the 4th International Pipeline Conference*. Alberta: American Society of Mechanical Engineers; p. 1501–1508.
- Kirkwood M, Fu B, Vu D, Batte A. 1996. Assessing the integrity of corroded linepipe—an industry initiative. In: *Proceedings of the Advances in Subsea Pipeline Engineering and Technology*. Aberdeen: Society of Underwater Technology; p. 55–68.
- Klever F, Stewart G, Valk C. 1995. New developments in burst strength predictions for locally corroded pipelines. New York (NY): American Society of Mechanical Engineers. Report no. CONF-950695.
- Kyriakides S, Babcock C. 1983. On the initiation of a propagating buckle in offshore pipelines. Hemisphere Publishing Corp; p. 187–199.
- Kyriakides S, Corona E. 2007. *Mechanics of offshore pipelines: volume 1 buckling and collapse*. vol. 1. Oxford: Elsevier.
- Lancaster E, Palmer S. 1996a. Burst pressures of pipes containing dents and gouges. *Proc Inst Mech Eng E.* 210:19–27.
- Lancaster E, Palmer S. 1996b. Strain concentrations in pressurized dented pipes. *Proc Inst Mech Eng E.* 210:29–38.
- Lee G, Pouraria H, Seo J, Paik J. 2015. Burst strength behaviour of an aging subsea gas pipeline elbow in different external and internal corrosion-damaged positions. *Int J Nav Arch Ocean Eng.* 7:435–451.
- Levold E, Marchionni L, Vitali L, Molinari C, Restelli A, Ozkan IF. 2013. Strength and deformation capacity of corroded pipe-laboratory tests and FEM analyses. In: *Proceedings of the Twenty-third International Offshore and Polar Engineering Conference*. Anchorage: International Society of Offshore and Polar Engineers; p. 1–9.
- Levold E, Restelli A, Marchionni L, Molinari C, Vitali L. 2013. Strength and deformation capacity of corroded pipes: The joint industry project. In: *Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering*. Nantes: American Society of Mechanical Engineers.
- Loureiro J, Netto T, Estefen S. 2001. On the effect of corrosion defects in the burst pressure of pipelines. In: *Proceedings of the 20th International Conference on Offshore Mechanics and Arctic Engineering*. New York (NY): American Society of Mechanical Engineers.
- Macdonald K, Cosham A. 2005. Best practice for the assessment of defects in pipelines—gouges and dents. *Eng Fail Anal.* 12:720–745.
- Mohd M, Kim D, Lee BJ, Kim D, Seo J, Paik J. 2014. On the burst strength capacity of an aging subsea gas pipeline. *J Offshore Mech Arct Eng.* 136:041402.
- Mohd MH, Lee BJ, Cui Y, Paik JK. 2015. Residual strength of corroded subsea pipelines subject to combined internal pressure and bending moment. *Ships Offshore Struct.* 10:554–564.
- Murphey C, Langner C. 1985. Ultimate pipe strength under bending, collapse and fatigue. In: *Proceedings of the 4th International Conference on Offshore Mechanics and Arctic Engineering*. New York (NY): American Society of Mechanical Engineers. Vol. 1. p. 467–477.
- NEB, Murray D, Souza L. 1994. Prediction of wrinkling behavior of girth-welded line pipe. Report no. 197.
- Netto T, Ferraz U, Botto A. 2006. Residual strength of corroded pipelines under external pressure: a simple assessment. In: *Proceedings of the International Pipeline Conference*. Alberta: American Society of Mechanical Engineers; p. 143–156.
- Ong L, Soh A, Ong J. 1992. Experimental and finite element investigation of a local dent on a pressurized pipe. *J Strain Anal Eng Des.* 27: 177–185.
- Orynyak, Rozhonyuk V, Shlapak L. 1999. Residual strength of pipelines with dents. *Mater Sci.* 35:689–694.
- Paik J. 2007. Ultimate strength of steel plates with a single circular hole under axial compressive loading along short edges. *Ships Offshore Struct.* 2:355–360.
- Pakiding L. 2007. Design criteria for high strength steel joints. [dissertation]. Delft: Delft University of Technology.
- Park T, Kyriakides S. 1996. On the collapse of dented cylinders under external pressure. *Int J Mech Sci.* 38:557–578.
- Pluvinage G. 2006. Pipe-defect assessment based on the limit analysis, failure-assessment diagram, and subcritical crack. *Mat Sci.* 42:127–139.
- Polenta V, Garvey S, Chronopoulos D, Long A, Morvan H. 2015. Optimal internal pressurisation of cylindrical shells for maximising their critical bending load. *Thin-walled Struct.* 87:133–138.
- Prabu B, Raviprakash A, Venkatraman A. 2010. Parametric study on buckling behaviour of dented short carbon steel cylindrical shell subjected to uniform axial compression. *Thin-Walled Struct.* 48:639–649.
- Rajabipour A, Melchers RE. 2015. Capacity of pitting corroded pipes under hydrogen assisted cracking. *Int J Hydrogen Energy.* 40:9388–9399.
- Ramberg W, Osgood W. 1943. Description of stress-strain curves by three parameters. Washington (DC).
- Riks A, Rankin C, Broan F. 1992. The buckling of a central crack in a plate under tension. *Eng Fract Mech.* 26:1023–1042.
- Riks E. 1972. The application of Newton's method to the problem of elastic stability. *J Appl Mech.* 39:1060–1065.
- Riks E. 1979. An incremental approach to the solution of snapping and buckling problems. *Int J Solids Struct.* 15:529–551.
- Seng O, Wing C, Seet G. 1989. The elastic analysis of a dent on pressurized pipe. *Int J Pres Ves Pip.* 38:369–383.
- Silva J, Ghaednia H, Das S. 2012. Fatigue life assessment for NPS30 steel pipe. In: *Proceedings of the 9th International Pipeline Conference*. Alberta: American Society of Mechanical Engineers. p. 619–624.
- Song C, Teng J, Rotter J. 2004. Imperfection sensitivity of thin elastic cylindrical shells subject to partial axial compression. *Int J Solids Struct.* 41:7155–7180.
- Starnes JH, Rose C. 1998a. Buckling and stable tearing responses of unstiffened aluminum shells with long cracks. In: *Proceedings of the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference and Exhibit*. Hampton: NASA Langley Research Center; p. 20–23.
- Starnes JH, Rose CA. 1998b. Nonlinear response of thin cylindrical shells with longitudinal cracks and subjected to internal pressure and axial compression loads. In: *Proceedings of the NASA Conference Publication*. Hampton: NASA; p. 197–208.
- Szary T. 2007. The finite element method analysis for assessing the remaining strength of corroded oil field casing and tubing [dissertation]. Germany: Freiberg University.
- Tam C, Raven P, Robinson R, Stensgaard T, Al-Sharif A, Preston R. 1996. Oman India pipeline: development of design methods for hydrostatic collapse in deep water. In: *Proceedings of the Offshore Pipeline Technology Conference*. IBC Technical Services Limited; p. 1–17.
- Timoshenko S, Gere J. 2009. *Theory of elastic stability*. New York (NY): Courier Corporation.
- Vasilikis D, Karamanos S, Es S, Gresnigt A. 2015. Ultimate bending capacity of spiral-welded steel tubes—part ii: predictions. *Thin-Walled Struct.* 102:305–319.

- Vaziri A, Estekanchi H. 2006. Buckling of cracked cylindrical thin shells under combined internal pressure and axial compression. *Thin-Walled Struct.* 44:141–151.
- Vedeld K, Sollund H, Hellesland J, Fyrileiv O. 2014. Effective axial forces in offshore lined and clad pipes. *Eng Struct.* 66: 66–80.
- Vitali L, Bartolini L, Askheim D, Peek R, Levold E. 2005. Hotpipe JI project: experimental test and FE analyses. In: *Proceedings of the 24th International Conference on Offshore Mechanics and Arctic Engineering*. Halkidiki: American Society of Mechanical Engineers; p. 715–729.
- Westergaard H. 1952. *Theory of elasticity and plasticity*. Vol. 367. Cambridge (MA): Harvard University Press.
- Yeh M, Kyriakides S. 1986. On the collapse of inelastic thick-walled tubes under external pressure. *J Energy Resour Technol.* 108: 35–47.
- Yeh M, Kyriakides S. 1988. Collapse of deepwater pipelines. *J Energy Resour Technol.* 110:1–11.
- Yudo H, Yoshikawa T. 2015. Buckling phenomenon for straight and curved pipe under pure bending. *J Mar Sci Technol.* 20: 94–103.
- Zecheru G, Yukhymets P, Draghici G, Dumitrescu A. 2015. Methods for determining the remaining strength factor of pipelines with volumetric surface defects. *Rev Chim.* 66:710–717.
- Zerbst U, Ainsworth R, Beier HT, Pisarski H, Zhang Z, Nikbin K, Nitschke-Pagel T, Münstermann S, Kucharczyk P, Klingbeil D. 2014. Review on fracture and crack propagation in weldments – a fracture mechanics perspective. *Eng Fract Mech.* 132:200–276.
- Zhang S, Chen X, Wang X, Hou J. 2015. Modeling of burst pressure for internal pressurized pipe elbow considering the effect of yield to tensile strength ratio. *Meccanica.* 50:2123–2133.
- Zhao K, Wang L, Chang Y, Yan J. 2016. Identification of post-necking stress-strain curve for sheet metals by inverse method. *Mech Mater.* 92:107–118.
- Zheng M, Li J, Shu X. 2005. Modified expression for predicting the bending resistance of a locally corroded pipeline and its experimental verification. *Met Mater Int.* 11:215–219.
- Zhou Z, Murray D. 1993. *Numerical structural analysis of buried pipelines*. Alberta: University of Alberta. Report no. 181.
- Zingoni A. 2015. Liquid-containment shells of revolution: a review of recent studies on strength, stability and dynamics. *Thin-Walled Struct.* 87:102–114.