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A simplified formula for calculating the limit load of cracked offshore wind turbine monopile under bending

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ABSTRACT

A simplified methodology is proposed for calculating the plastic collapse (limit) bending moment load of a pipe with a circumferential flaw with an emphasis on its application for use in the assessment of cracked offshore wind turbine monopile using failure assessment diagrams. The proposed methodology is based on the theory of net section collapse (NSC) but differs from existing approaches in that it does not need idealisation and categorisation of the crack before assessment. The proposed methodology is validated against results presented in literature and also finite element analysis results. Although it is possible to obtain limit loads using FE analysis, this is computationally expensive and time consuming. The proposed approach allows for near-instantaneous calculation of limit load for any arbitrary crack configuration and loading direction. This is a significant development for the analysis of offshore wind turbine monopiles as it allows the suitability of the cracked structure to be assessed in pseudo-real time.

1. Introduction

In 2016, 12% of the installed wind turbine capacity in Europe was older than 15 years. This share increases to 28% by 2020. These wind turbines will soon reach the end of their designed service life, which is typically 20 years. As a consequence, the wind industry needs to prepare for upcoming challenges such as, maintenance of aging assets, assessment of structural integrity, lifetime extension decision making, and decommissioning of turbines [1].

An aged structure is likely to already contain a flaw either due to manufacturing defects or through system loading. It is therefore necessary to assess its fitness for service to ascertain if the cracked structure will fail under applied load. One widely accepted method for assessing the acceptability of a flaw in a metallic structure is to plot its position on the failure assessment diagram (FAD) as prescribed in the industry standards such as BS 7910 - Guide to methods for assessing the acceptability of flaws in metallic structures [2].

The FAD delineates regions of safe operation based on data for different materials. The ordinate plots the fracture ratio, K_r; a measure of the susceptibility of the structure's unstable brittle fracture calculated using linear elastic fracture mechanics. The abscissa plots the load ratio, L_r; a measure of the susceptibility of the structure to plastic collapse as is typical of less brittle or ductile materials where the microstructure allows for deformation/flow of the material.

The load ratio, L_r is the ratio of the applied load to the limit load for a particular cracked component. Therefore, the accurate calculation of plastic limit loads is a cornerstone for assessing the acceptability of a cracked structure.

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The limit load of a cracked structure may be determined from elastic-perfectly-plastic 3D finite element (FE) analyses. To do this, an elastic-perfectly-plastic material curve is assumed with the onset of plasticity set as the flow strength. Incremental load is applied to the structure until the magnitude of the applied load that causes global plastic collapse is achieved. This is signalled by the loss of static structural equilibrium due to excessive plasticity. The load applied at the final converged increment is the limit load [3].

The limit load analysis must be repeated if there is any change in the configuration. It is computationally expensive to set up and run these FE models. Thus, finite element analysis is not practical in situations where the crack geometry is constantly changing under the action of fatigue loads.

Hence, a more efficient approach is required for the estimation of limit load for real time/pseudo-real time assessment of a cracked offshore wind turbine monopile subjected to cyclic loading. The objective of this paper is to introduce a more suitable and efficient methodology. It is noted that the proposed methodology is intended for use in the determination of load ratio, L_r for failure assessment diagram. The FAD approach is established and enshrined within international standards and design guidance such as BS7 910 [2]. The contribution made in this paper is in a better understanding and calculation of L_r for large diameter tubulars for use within the FAD framework and does not attempt to distinguish between ductile-brittle behaviour which is dealt with elsewhere.

The remainder of this paper is organized as follows: Section 2 presents the formulation of the proposed approach. The validation of the methodology is presented in section 3. The results are discussed in section 4. The conclusions and outlook are presented in section 5.

2. Net section collapse

Net section collapse (NSC) is a simple method originally developed in the Electric Power Research Institute (EPRI) project RP585 [4] for determining the collapse load of a cracked pipe containing circumferential cracks. This approach is adopted by a wide range of industrial standards such as [5].

NSC analysis of cracked pipes in accordance with industrial standards typically involves idealisations of the crack geometry. For most applications, a crack is often idealised as either a semi-elliptical or constant depth. Rahman and Wilkowski [6] extended the NSC methodology to symmetrical flaws with complex shapes. Iwamatsu et al. [7] extended the methodology to allow non-symmetric flaws to be assessed by adding continuous shift angle. The shift angle allows the position of the coordinate axes which produce the minimum failure bending moment to be established. Several researchers such as Hasegawa et al. [8] and Iwamatsu et al. [9] have validated the use of NSC to determine the limit load of small diameter cracked pipes. This includes experimental validation against 304 stainless steel pipe with various number of circumferential cracks.

To the best of the of the author's knowledge, most research to validate NSC equations such as [8–11] have focused on small pipes (circa 114.3mm in diameter). There is little work validating the use of the NSC equations for use with large diameter cylinders. The NSC equations derived in this paper are intended for use with offshore wind turbine (OWT) monopile support structures which represent approximately 90% of commissioned offshore wind structures [12] and can be 6m in diameter [13]. OWT monopiles are fabricated by rolling and then welding thick structural steel plates in the longitudinal direction to produce "cans" which are then welded together circumferentially. Cracks in monopiles typically start from a surface flaw situated at the weld/parent metal interface. The crack grows gradually and may penetrate the wall thickness over time.

Literature review indicates that net section collapse equations are typically generated for two conditions: entire crack is subjected to tension or crack is partially subjected to compression. The case where part of the crack is in compression is further divided into cases with crack closure and non-crack closure corresponding to geometries with tight and blunt cracks, respectively. The user must first categorise the crack to allow the selection of the appropriate set of equations.

In this paper a generalised equation is formulated that is considered suitable for the limit load analysis of any crack located in either the tensile or compressive zones as long as the crack is capable of crack closure. For monopiles under compressive loads, the crack faces come into contact to transmit loads. This is a primary reason why the cracks do not grow when the stress is compressive. Thus, for these

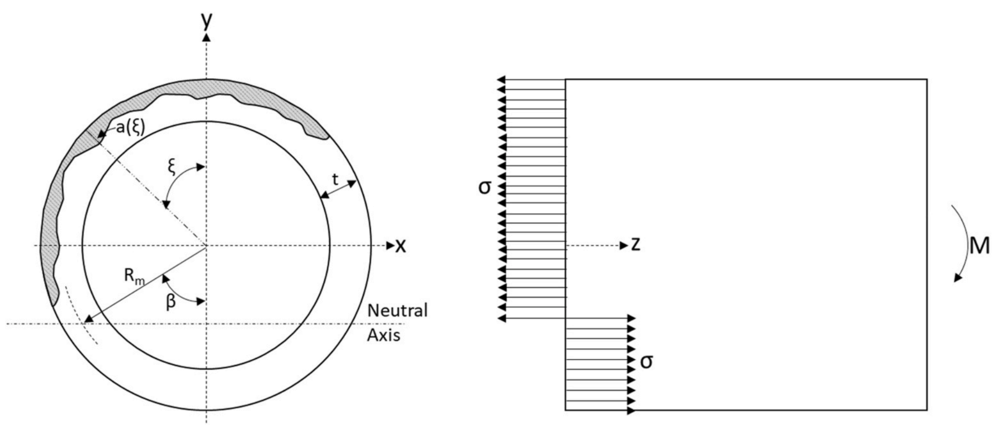


Fig. 1. Crack geometry and stress distribution.

structures, behaviour under crack non-closure is not relevant.

2.1. Equation formulation

The internal stress distribution (σ) in the wall of a pipe with external surface cracks is presented in Fig. 1. The cracks are assessed for Mode I loading which is typical for most fractures. For a crack subject to Mode I loading, the principal load is applied normal to the crack and tends to open the crack. Although the offshore wind turbine monopile is subject to various types of loads; compressive loads, shear forces and torsion, only bending moment loads are applicable to Mode I crack opening.

The cracks shown in Fig. 1 are not symmetrical about the bending plane. The lack of symmetry means that the internal bending moment will have components in both x and y axes, thus, when the moments are integrated, they may not equate to the externally applied uniaxial bending moment. However, work by multiple researchers such as [7] show that the minimum collapse load occurs when the axis of the applied bending moment is symmetric with respect to the crack. Therefore, to obtain the minimum collapse capacity, the NSC assessment should consider load applied at the symmetric axis regardless of the actual bending axis.

Two key parameters are noted in Fig. 1; the location of the neutral axis (N.A) which denote the line of zero stress due to applied bending load and the associated stress inversion angle β.

A couple of simplifications are adopted for the purpose of generating the NSC equations. They are as follows:

- It is assumed that the pipe can be classified as thin walled. For practical engineering applications, thin-walled assumption is adopted for pipes with ratio of diameter to thickness (D/t) greater than twenty. D/t for monopiles used in commercial OWT are in excess of this value [13].
- For a monopile containing multiple co-planer cracks, the cracks are treated as a single crack spanning the entire circumference of the pipe. The crack depth is simply set to zero for the uncracked regions. The manipulation of the crack geometry in this manner removes the need to define the integration limit for each individual crack.

For application of bending moment about an axis that is symmetric with respect to the crack profile, the internal stress system must satisfy equilibrium with the applied loads.

The monopile is only subjected to compressive load due to the weight of the tower, nacelle, and rotors. Thus, the equation for tensile force equilibrium is as follows:

$$\sigma R_m t\left[\int_0^{\pi-\beta}\left(1-\frac{a(\xi)}{t}\right)d\xi+\int_{\pi+\beta}^{2\pi}\left(1-\frac{a(\xi)}{t}\right)d\xi-2\beta\right]=0$$

Re-arranging gives:

$$\beta=\frac{\boldsymbol{\pi}}{2}-\frac{1}{4\boldsymbol{t}}\left[\int_0^{\pi-\beta}\boldsymbol{a}(\boldsymbol{\xi})\boldsymbol{d\xi}+\int_{\pi+\beta}^{2\pi}\boldsymbol{a}(\boldsymbol{\xi})\boldsymbol{d\xi}\right] \tag{1}$$

The monopile is subjected to a moment load due to wind loads on the tower and the nacelle. Thus, to satisfy moment equilibrium:

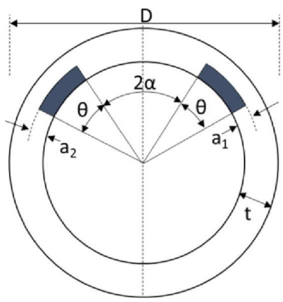
$$\sigma R_m{}^2 t\left[4sin\beta-\frac{1}{t}\left[\int_0^{\pi-\beta}a(\xi)cos\xi d\xi+\int_{\pi+\beta}^{2\pi}a(\xi)cos\xi d\xi\right]\right]=M \tag{2}$$

For a crack with a complex shape, it is not possible to define a closed function for the crack depth "a", and thus obtain an analytic solution for the integral in equations (1) and (2). However, obtaining a solution by numerical analysis is trivial.

Setting the internal stress (σ) to the flow stress of the material (σ_f) allows the calculation of the maximum moment that the structure

Table 1
Pipe Specimen Geometries [8].

Specimen No.	D (mm)	t (mm)	Flaw Depths a1 (mm)	a2 (mm)	Angle θ (deg)	α (deg)
DP 01	114.3	8.6	6.3	6.3	60	0
DP 02			6.4	6.4	60	10
DP 03			6.3	6.2	60	20
DP 04			6.4	6.2	60	30
DP 05			6.3	6.2	45	30
DP 06			6.3	6.3	45	40



can withstand before plastic collapse. The collapse bending moment is obtained by solving equation (1) to obtain the value of β for the cracked geometry. β is then used in equation (2) to obtain the collapse moment.

3. Validation of proposed methodology

3.1. Literature

Limit load values obtained using the methodology presented above are compared to values found in literature. Hasegawa et al. [8] performed theoretical calculations and also obtained experimental values for geometries containing constant depth, internal circumferential flaws with a material flow strength of 425 MPa. The geometry considered in the research work is summarized in Table 1.

Fig. 2 shows that the proposed methodology agrees with the calculated values from Hasegawa et al. [8]. Both calculated values are correlated well (<10% difference) with the experimental results thus validating the NSC approach for limit load calculation

3.2. Finite element analysis

The validation case presented in section 3.1 is based on a small diameter pipe. There is a valid question concerning the applicability of Net Section Collapse to large diameter cracked pipe. Due to the scale of the geometry, it is not practical to perform physical testing to obtain limit loads of cracked monopiles. An alternative method for systematic validation is to use finite element (FE) analysis.

FE limit load analysis is a well-established method for predicting plastic collapse. The process involves the application of an elastic-perfectly-plastic material curve to the structure with the onset of plasticity set as the material flow strength. Incremental load is applied to the structure until the structure cannot carry more load. This is signalled by the loss of static structural equilibrium. The load applied at the final converged increment is the limit load [14]. Confidence in the FE limit analysis is gained by comparing results obtained against the idealised plastic limit load solutions for uncracked pipe.

The monopile used for validation has an outer radius, r_o of 3m, inner radius, r_i of 2.9m and wall thickness, t of 100mm in line with typical sizes of existing monopiles in various wind farms across Europe as reported in Ref. [13]. The length of the monopile is set as 40m which is the typical water depth of monopile foundation installations [15]. S355 steel is the most common material used in the fabrication of monopile support structure [16]. The material properties for S355 steel are as follows; the minimum yield strength, σ_Y is taken as 335MPa, the tensile strength, σ_u is taken as 470Mpa, the modulus of elasticity, E is 210Gpa [17]. The flow strength is taken as 402.5Mpa which is the average of the yield and ultimate tensile strength.

The monopile is modelled in the finite element software package, ABAQUS [18]. The FE model is pinned at one end. The moment load is applied to a reference point coupled to the free surface generating a pure bending load in the monopile. The crack is located at the longitudinal midspan of the monopile. The reader is directed to the Abaqus manual [18] for further discussion on crack modelling within the software. To avoid problems associated with incompressibility, quadratic reduced integration elements within ABAQUS (element type: C3D20R) are used [19]. A schematic FE model is presented Fig. 3. The implementation of the boundary condition and reference point for moment load application is shown in Figure 3a. The variation of element size around the crack region is shown in Fig. 3b and in Fig. 3c.

4. Results and discussion

The results of the FE analysis validation for various crack cross-sections using the pipe geometry is presented below. Firstly, the proposed methodology is validated against cracks of various depth/pipe thickness (a/t) ratios, and half angle, θ. Each crack is a constant depth external surface crack and symmetrical about the applied moment axis.

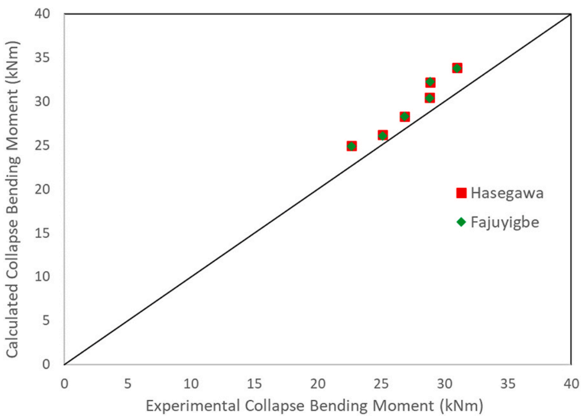
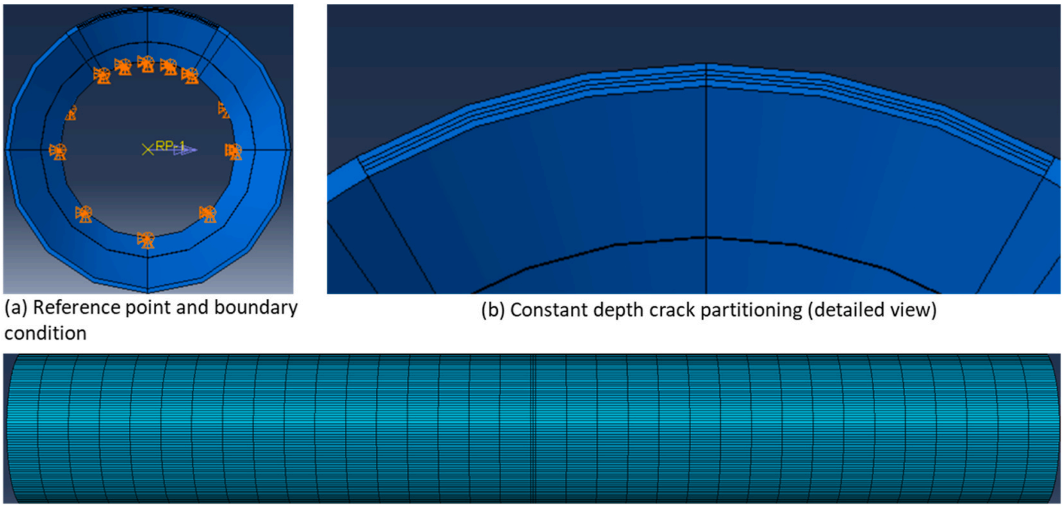


Fig. 2. Comparison of Collapse Moment using Proposed Methodology and Hasegawa Data [8].

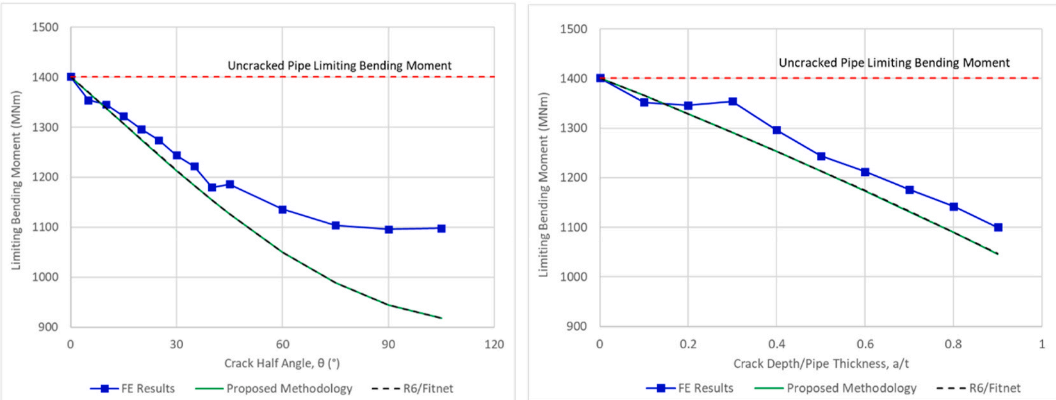


(a) Reference point and boundary condition

(b) Constant depth crack partitioning (detailed view)

(c) Mesh side view and mid-length partitioning

Fig. 3. Finite Element Model & Crack Depth Distribution vs angle.



(a) Varying crack half angle (θ) for fixed crack depth/pipe thickness (a/t = 0.5)

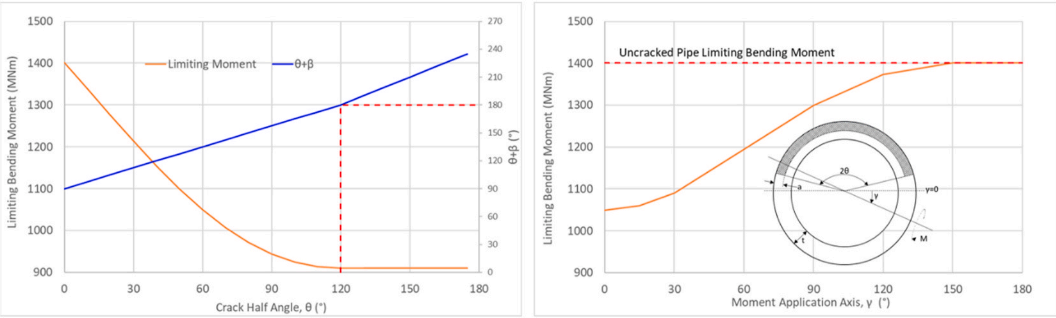
(b) Varying crack depth/pipe thickness (a/t) for a fixed crack half angle (θ=30°)

Fig. 4. Limiting bending moment for various crack geometry.

Fig. 4 shows that the proposed methodology gives the same outcome as results obtained from the application of the widely accepted R6/Fitnet procedures [5]. The results using the proposed methodology are also similar to the values obtained from FE analysis with a maximum deviation below 10% for crack half angles below 60°. The deviation increases as the crack becomes very large relative to the pipe. This points to some limiting condition for the applicability of Net Section Collapse theory to obtain limit loads for cases where the crack is very large relative to the monopile section. However, the likelihood of such cracks existing in reality is questionable given the increased risk of brittle fracture for large cracks.

Furthermore, the limiting loads from FE analysis are consistently larger indicating that results obtained from the proposed methodology are conservative. This is consistent with literature [19] [20] as well as limit loads obtained from the industry code R6 [5]. It is known that these analytical solutions derived from simple equilibrium stress fields and yield criterion such as Tresca or Von Mises tend to under-predict actual limit loads, but the degree of conservatism is difficult to quantify. The conservatism in predicting plastic collapse loads using these methods may be one reason for their adoption as they should inherently lead to a safe design.For all cases, the plastic limit load defaults to the uncracked pipe value when θ or $a/t = 0$ granting confidence in the methodology.

One advantage of the proposed methodology over the existing approaches is that there is no need to categorise cracks into those entirely in the tension zone and those straddling the compression zone. In existing approaches, the categorisation is then used to select the appropriate equations to determine the limit load of the cracked geometry. Mathematically, the categorisation is implemented by checking if $\theta+\beta \leq$ or $\geq \pi$. This is problematic as β is in itself an outcome of the net section collapse calculations. The proposed



(a) Analysis of cracks in tension and compression zone

(b) Limiting bending moment for various load axis

Fig. 5. Capability of new methodology.

methodology is valid for cracks located in both the tension and compression zone as is shown in Fig. 5(a). The plot shows that the limit load plateaus as $\theta+\beta > \pi$. This is because part of the crack is now in the compression zone and is able to transmit load in the same manner as an uncracked pipe.

Another advantage of the proposed methodology is the ability to determine the limiting bending moment applied at an axis that is not symmetrical to the crack profile. The practical implication is that limiting load can be determined for loading applied to the pipe in any arbitrary direction. This is particularly useful for offshore wind turbine monopile where environmental loads affect the structure from various directions. As shown in Fig. 5(b), the limiting bending moment increases as more of the crack profile moves into the compression zone relative to the axis of the applied moment. The limiting moment reaches the value for uncracked pipe when the axis of the applied moment is oriented such that the applied moment tends to close the crack ($\gamma = 180°$).

4.1. Variable crack analysis

Current NSC design guidelines such as R6/Fitnet [5] require a crack to be categorised as either semi elliptical or constant depth for the estimation of plastic limit load. Real cracks can have an arbitrary profile. Crack shape idealisations such as semi-elliptical or constant depth can lead to under estimation of the plastic collapse load. Cracks with arbitrary shaped profile can be assessed using the methodology proposed in this paper.

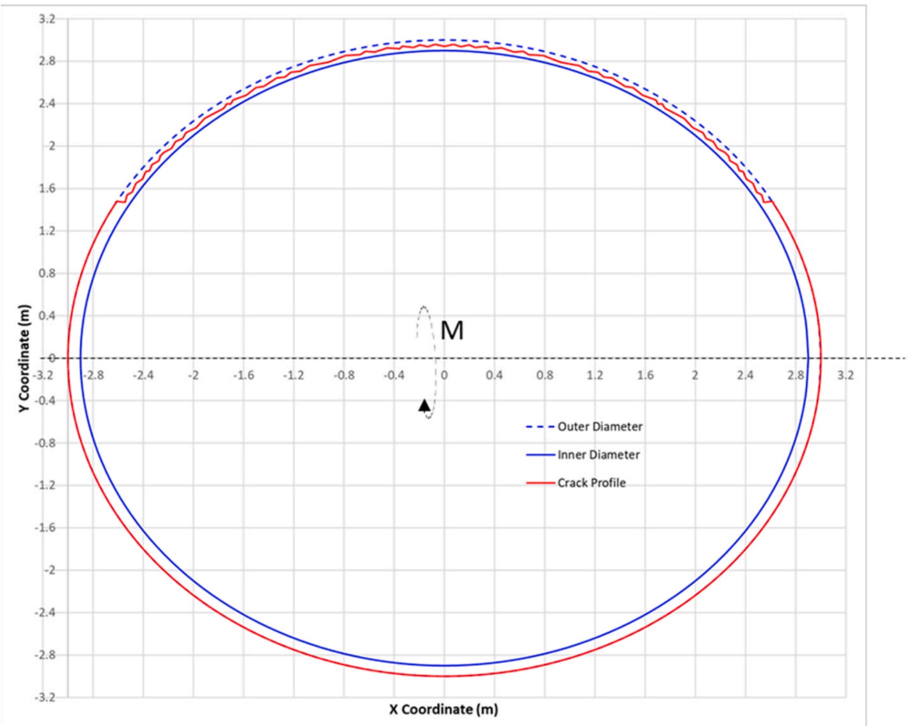


Fig. 6. Variable crack profile.

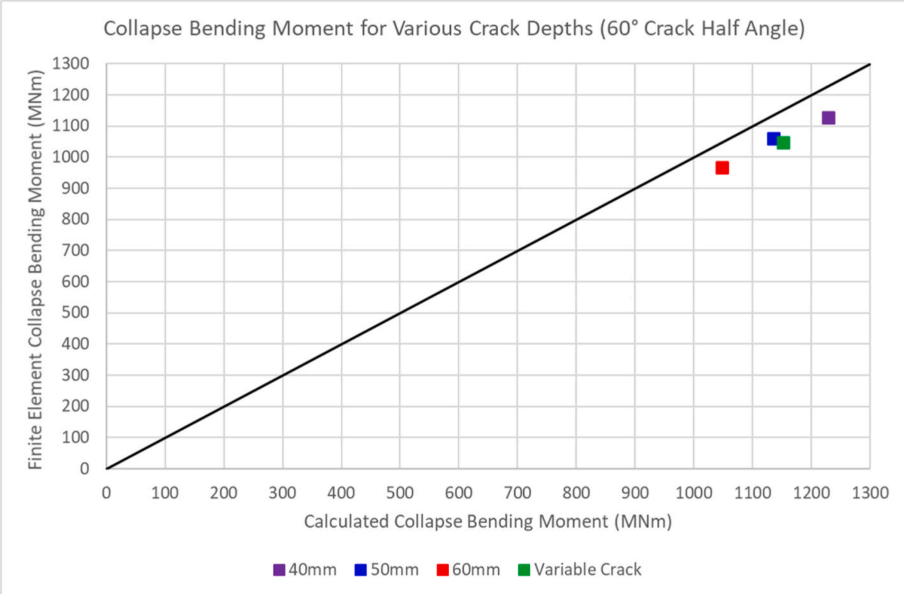


Fig. 7. Variable crack results.

A crack with a variable depth is modelled in the monopile geometry presented above. The crack depth/pipe thickness ratio (a/t) varies between a/t of 0.4 and 0.6. The crack's half angle (θ) is 60°.

The crack profile is illustrated in Fig. 6. The limit bending moment obtained from calculations and finite element analysis are presented in Fig. 7. Results are presented for constant cracks with a/t of 0.4, 0.5, 0.6 and the variable crack in Fig. 7. All cracks have a half angle (θ) of 60°. The results show that limit load for a crack with variable depth is between the bounding limits of results for a/t = 0.4 and a/t = 0.6. The results for the variable crack are also similar to the results for a constant crack with a/t = 0.5. This is also expected as the area of loss ligament for the variable is equivalent to a constant crack depth with a/t = 0.495. From the comparison, it is clear that the plastic collapse bending moment load for a variable crack is well predicted by the methodology proposed in this paper.

5. ConclusionS

This paper presents a methodology for calculating the plastic collapse (limit) bending moment load of a pipe with a circumferential flaw with an emphasis on its application in the assessment of cracked offshore wind turbine monopiles. The limit load is a key component of the calculation of the load ratio which is used in the assessment of the fitness for purpose of a cracked structure. The methodology proposed in this paper is based on the theory of net section collapse (NSC) but differs from existing approaches in the following ways:

- The crack does not need to be categorised as occupying the tensile or compression zone.
- For multiple cracks, there is no need to define the span limits of each individual crack in the pipe geometry.
- The crack shape does not need to be idealised as either semi-elliptical or constant depth.
- The crack does not need to be symmetrical about the axis of the applied bending moment.

The proposed methodology is validated against results presented in literature and also finite element analysis results. Although it is possible to obtain limit loads using FE analysis, this is computationally expensive and time consuming. The proposed approach allows for near-instantaneous calculation of limit load for any arbitrary crack configuration and loading direction. This is a significant development for the analysis of offshore wind turbine monopiles as it allows the suitability of the cracked structure to be assessed in pseudo-real time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Ziegler L, Gonzalez E, Rubert T, Smolka U, Melero JJ. Lifetime extension of onshore wind turbines: a review covering Germany, Spain, Denmark, and the UK. Renew Sustain Energy Rev 2018;82:1261–71.
[2] Standard B. BS 7910: 2013+ A1: 2015 Guide to methods for assessing the acceptability of flaws in metallic structures. London, UK: BSI Stand Publ; 2015.
[3] Fajuyigbe A, Brennan F. Fitness-for-purpose assessment of cracked offshore wind turbine monopile. Mar Struct 2021;77:102965.
[4] Kanninen MF, et al. Mechanical fracture predictions for sensitized stainless steel piping with circumferential cracks. Battelle Columbus Labs.; 1976.
[5] R6. Assessment of the integrity of structures containing defects. Br Energy Gener Rep R/H/R6, Rev 2001;4.
[6] Rahman S, Wilkowski G. Net-section-collapse analysis of circumferentially cracked cylinders—part I: arbitrary-shaped cracks and generalized equations. Eng Fract Mech 1998;61(2):191–211.
[7] Iwamatsu F, Miyazaki K, Saito K, Hamanaka T, Takahashi Y. Estimation of Maximum Load For Pipes With Multiple Circumferential Flaws By Limit Load Analysis, 44519; 2011. p. 503–10.
[8] Hasegawa K, Saito K, Iwamatsu F, Miyazaki K. Prediction of fully Plastic Failure Stresses For Pipes With Multiple Circumferential Flaws, 42797; 2007. p. 415–9.
[9] Iwamatsu F, Miyazaki K, Saito K, Hasegawa K. Experimental Estimation Of Fully Plastic Collapse Stresses For Pipes With Three Circumferential Flaws, 43642; 2009. p. 223–7.
[10] Li Y, Hasegawa K, Onizawa K, Cofie NG. Prediction of collapse stress for pipes with arbitrary multiple circumferential surface flaws. J Pressure Vessel Technol 2010;132(6).
[11] Li Y, Azuma K, Hasegawa K. Failure bending moment of pipes containing multiple circumferential flaws with complex shape. Int J Pres Ves Pip 2019;171: 305–10.
[12] Brennan FP. A framework for variable amplitude corrosion fatigue materials tests for offshore wind steel support structures. Fatig Fract Eng Mater Struct 2014; 37(7):717–21.
[13] Arany L, Bhattacharya S, Macdonald J, Hogan SJ. Design of monopiles for offshore wind turbines in 10 steps. Soil Dynam Earthq Eng 2017;92:126–52.
[14] Booth MR. Applying finite element based limit load analysis methods to structures under dynamic loads. V001T01A005 Am Soc Mech Eng 2014;45981. 2014.
[15] Bocher M, Mehmanparast A, Braithwaite J, Shafiee M. New shape function solutions for fracture mechanics analysis of offshore wind turbine monopile foundations. Ocean Eng 2018;160:264–75.
[16] Igwemezie V, Mehmanparast A, Kolios A. Materials selection for XL wind turbine support structures: a corrosion-fatigue perspective. Mar Struct 2018;61: 381–97.
[17] En. Eurocode 3: design of steel structures: general rules and rules for buildings. In: CEN, European Committee for Standardization Brussels; 2005.
[18] User Manual. (2016). [SIMULIA].
[19] Kim Y-J, Shim D-J, Nikbin K, Kim Y-J, Hwang S-S, Kim J-S. Finite element based plastic limit loads for cylinders with part-through surface cracks under combined loading. Int J Pres Ves Pip 2003;80(7–8):527–40.
[20] Eren ŞE, London T, Yang Y, Hadley I. Validation of plastic collapse assessments using BS 7910: 2013 and R6 procedures. Am Soc Mech Eng 2013;55645. V01BT01A027.