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Publication date
2018

Document Version
Final published version

Published in
Proceedings of the 32nd Asian-Pacific Technical Exchange and Advisory Meeting on Marine Structures (TEAM 2018)

Citation (APA)
Li, Z., Jiang, X., & Hopman, H. (2018). Numerical investigation of the SIFs of the external surface crack in rigid pipe reinforced with FRP. In *Proceedings of the 32nd Asian-Pacific Technical Exchange and Advisory Meeting on Marine Structures (TEAM 2018)* (pp. 1-6)

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TEAM 2018, *Oct. 15 - 18, 2018, Wuhan, China*

Numerical investigation of the SIFs of the external surface crack in rigid pipe reinforced with FRP

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Abstract

Fatigue is one of the major challenges of offshore rigid pipes. The surface crack is the main manifestation. Fatigue cracks are evolved from surface cracks which are frequently appear in the external surface of rigid pipes. Under fatigue loads, the surface cracks may continue to propagate and finally develop into penetrated cracks, which may cause leakage and serious accidents.

Fiber-reinforced polymer (FRP) strengthening technology is already a reliable technique for structure maintenance in onshore pipelines and penetrated cracks in load-bearing circular hollow sections (CHS). Nevertheless, the research gap of surface crack in rigid pipes reinforced with FRP is seriously restricting the development of FRP reinforcement application.

This paper aims to investigate the surface crack growth in the external surface of rigid pipes reinforced with FRP under bending. Stress intensity factors along the crack front are computed through finite-element (FE) models. The numerical results show that under FRP reinforcement, surface crack growth rate decreases significantly which ensures the safety use of rigid pipes in offshore industry.

Keyword: offshore rigid pipe, external surface crack, stress intensity factor, finite element method

NOMENCLATURE

CFRP	Carbon Fiber-reinforced Polymer
CRS	Composite Repair System
FE	finite element
FEM	finite element method
FRP	Fiber-reinforced Polymer
SIF	Stress Intensity Factor
UD	Uni-direction
E_a	elastic modulus of adhesive
E_i	elastic modulus of fiber in i direction
G_{ij}	shear modulus
Nu_{ij}	passion ratio
t	thickness
R_s	outer radius of rigid pipe
t_n	nominal stress normal mode only
t_s, t_t	nominal stresses in shear direction
K_{nn}	elastic stiffness of the adhesive in normal direction
K_{ss}, K_{tt}	elastic stiffness of the adhesive in shear directions
X^T, X^C	ultimate in-plane strength in fiber direction
Y^T, Y^C	ultimate in-plane strength in transverse direction

1. INTRODUCTION

The offshore rigid pipe is one of the most widely used pipes in offshore oil and gas industries, owning to their advantages of cost-effective, ease of installation and maintenance [1]. In the harsh environment, the rigid pipes bear marine dynamic loads long-termly, making the fatigue problem a major issue [2-4]. For instance, Fig. 1 shows two typical layouts of the offshore rigid pipes, the J-shape and the S-shape. The critical areas marked by red cycles suffer fatigue problems seriously under marine dynamic tension and bending loads, which can be generated by wave, current, wind, and 2nd order floater motions [1, 5]. As the main consequence of the fatigue problem, surface cracks frequently initiate in rigid pipes [6-8]. They may continually propagate during the reeling, installation and operation procedure, which brings a huge threat to the operation safety [8].

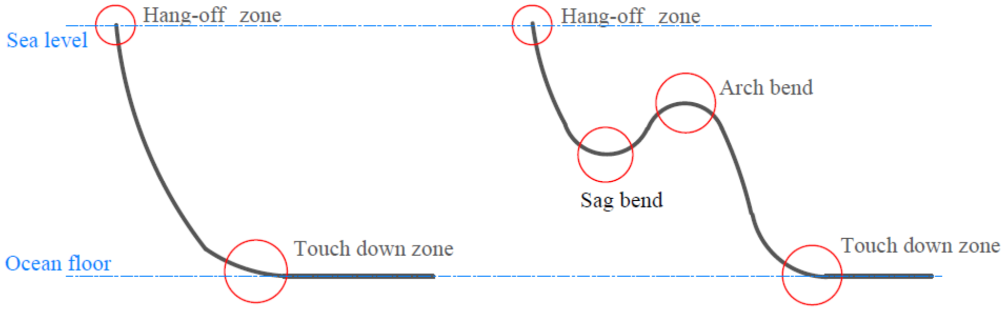


Fig. 1 *Critical areas of J-shape and S-shape layouts of offshore rigid pipes*

The propagation of surface cracks will eventually result in through-thickness cracks, which may cause leakage and other serious consequences. Therefore, preventing leakage due to surface crack propagation is of great importance. In practice, periodical inspections are carried out to detect the size and the location of surface cracks in offshore rigid pipes [7-8]. After that, the cracks will be reinforced by different reinforcement techniques.

Composite repair system is an advanced maintenance technique in pipeline industry as a particular application case of metallic structures reinforced with Fiber-reinforced polymer (FRP) [9-11]. The investigation of enhancing the pipe strength or repairing the through-thickness cracks were widely conducted by researchers. However, since surface cracks are more commonly seen in rigid pipes and preventing leakage has a vital significance, reinforcing surface cracks deserves more attention. Jianjun Chen [12] conducted a numerical investigation of the SIF of longitudinal internal surface crack in pipe reinforced with hooped wrapped composite layers under internal pressure. The results indicated that composite reinforcement could significantly decrease the value of SIF. The authors of this paper investigated the circumferential surface crack growth in rigid pipe and proposed an analytical method to predict the surface crack growth. The circumferential internal surface cracks growth in rigid pipe reinforced with FRP were investigated by the authors as well [13].

To the knowledge of the authors, there are hardly any literatures of external surface crack in rigid pipes reinforced with FRP. In view of this, this paper conducts a numerical investigation to estimate the SIFs of circumferential external surface crack growth in rigid pipes under bending. In section 2, a three-dimensional FEM is built. In section 3, the surface crack growth reinforced with FRP is investigated, the reinforcement effectiveness is evaluated. Then in section 4, a parametric study is conduct, including two types of CFRP and adhesive. The Final conclusions of this paper are stated in section 5.

2. FINITE ELEMENT MODELS

The FE models of external surface crack in rigid pipe under 4-point bending are built, as is illustrated in Fig. 2. The circumferential external surface crack is a semi-elliptical crack located at the bottom of the rigid pipe. The length of the pipe L is 2000 mm. The inner span of the 4-point bending l is 850 mm while the external span L_a is 1900 mm. The material of the rigid pipe is API 5L X65, with the yield stress of 448 MPa, ultimate tensile strength is 531 MPa. The overall reinforcement length is 600 mm. The details of the materials and reinforcement can be seen in Table 1.

Table 1. *Material properties of adhesive - MBrace*

Parameters	E_a(GPa)	t_n, t_s, t (MPa)	K_{nn} (10^{13} N/mm^3)	K_{ss}, k_{tt} (10^{13} N/mm^3)	G_n (N/m)	G_s, G_t (N/m)
Adhesive	2.86	46	2.8	1.4	1000	1250

Table 2. *Material properties of CFRP UD*

Parameters	E_1 (GPa)	E_2 (Gpa)	G_{12} (Pa)	G_{13} (Pa)	G_{23} (GPa)	Nu_{12}	X^T	X^C	Y^T	Y^C
CFRP UD	205	25	1	1	3.0	0.33	2760	552	1	1

The FE models are built through the ANSYS 19.0 academic package. The pipe is longitudinal reinforced with CFRP. The thickness of the adhesive layer and each CFRP layer is set as 0.2 mm and 0.6 mm respectively. The rigid pipe, support units and load units are modelled using 10 nodes 3-D solid element (Solid187), the surface crack is modelled using 20 nodes 3-D solid element (Solid186). The connections between load/support units and rigid pipe surface are achieved by Conta174 and Targe170 element respectively. The load units are restrained to only have an in-plane motion along the vertical direction and the two support units are set as fixed supports.

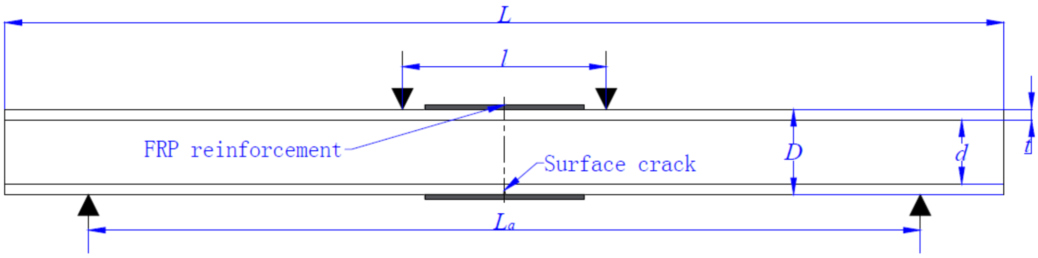


Fig. 2 *Sketch diagram of the FEM model set-up*

The circumferential surface cracks in rigid pipe are modelled as semi-elliptical shape, as is shown in Fig. 3. The FEM adopts appropriate meshing methods and refinement element sizes around the crack front to guarantee the accuracy. Fig. 4 shows the meshing condition of the reinforced pipe under 4-point bending. The pipe is modelled by three separate parts with different meshing method: tetrahedron meshing is applied for the middle part of the pipe where locates the surface crack, while sweep method is adopted for the other two parts of the pipe, as well as the adhesive layer and FRP layers, load units and the support units. The meshing method of the surface crack chooses the hex dominant method. The computational time is reduced by introducing 20 mm mesh size for pipe and load/support units, and 10 mm mesh size for the adhesive and the CFRP. Fig. 5 shows the modelling of the surface crack. For the mesh size of the surface crack, the crack front is divided into 15 parts, with 6 contours where the largest radius is 0.5 mm.

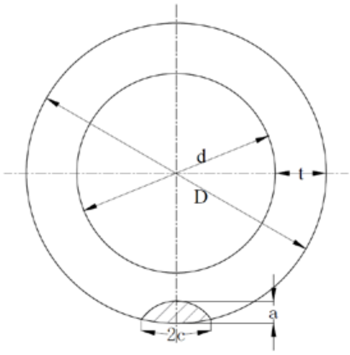
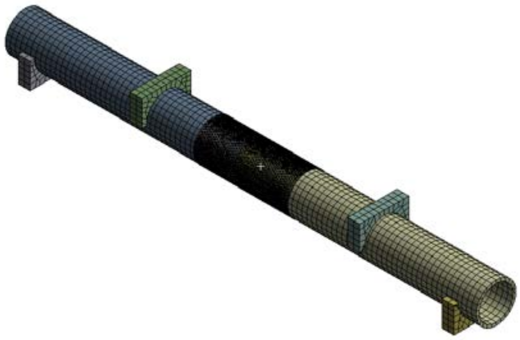


Fig. 3 *Sketch diagram of the external surface crack*



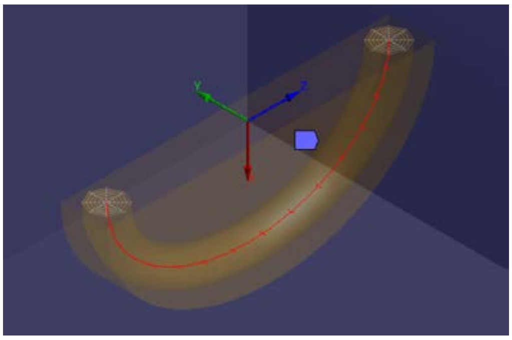


Fig. 4 *Meshing conditions of the pipe under 4-point bending* ***Fig. 5*** *Surface crack modelling*

3. SIF CALCULATION THROUGH FEM

The FEM is validated through available experimental results [14-15], which can be refer to Ref. [13]. In this section, the SIFs of three types of critical surface crack size in offshore rigid pipes [16] are analysis, as is shown in Table 3. The load level of is set as 250KN, which can generate 50% of the yield stress at the mid-span of the pipe.

Table 3. *Critical sizes of surface crack in 8" offshore rigid pipe*

Surface crack type	a (mm)	2c (mm)	a/c
1	3	25	0.24
2	4	20	0.40
3	5	15	0.67

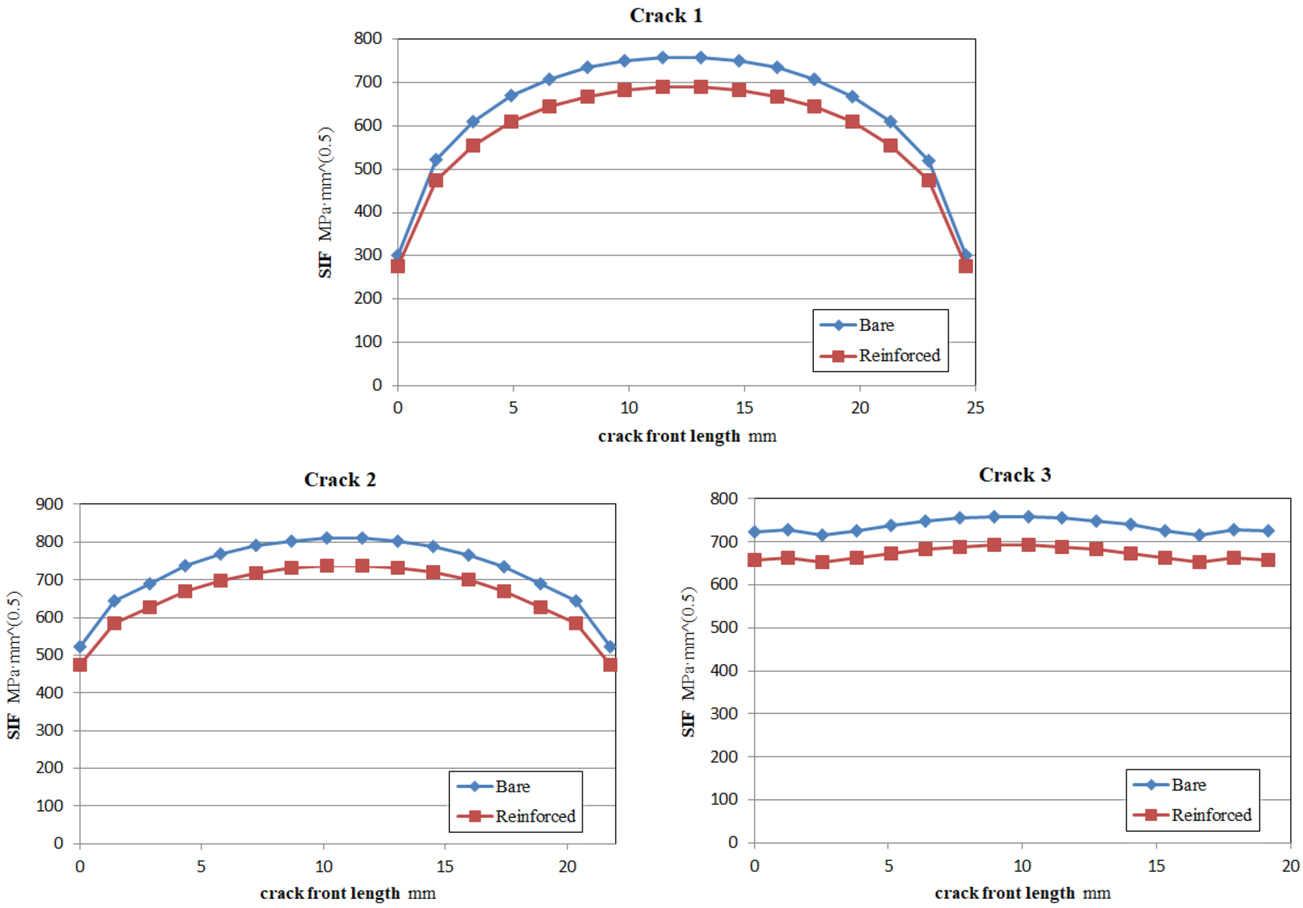


***Fig. 6** The comparison of the SIFs of three types of critical surface crack in the un-reinforced and reinforced pipe*

The rigid pipes are reinforced with three layers of longitudinal CFRP. The SIFs along the surface cracks are calculated through FEM, which is shown from Fig. 6. It can be clear seen that the SIFs along the surface crack decrease within the FRP reinforcement. The SIFs drop around 10%, which may decrease the crack growth rate of 30 - 40%, based on the material constants.

4. PARAMETRIC STUDIES

The CFRP reinforcement scheme such as layers, bond length and adhesive may influence the external surface crack growth in rigid pipe [14]. To understand the effects of those parameters in order to guide the CFRP reinforcement scheme, a range of parametric studies have been conducted using the corresponding validated FE models. The critical surface crack in this section chooses the 2nd type, with crack length of 20 mm and crack depth of 4 mm.

It is well known that increasing the CFRP layers, choosing CFRP with higher elastic modulus, and bond length can improve the effectiveness of the reinforcement [14]. This Section will investigate the influence of the CFRP type and the adhesive properties to the SIFs of the surface cracks.

4.1 CFRP type

Considering the practical application, it is feasible to wrap around the underwater rigid pipes with automatic wrapping machine. Therefore, the woven type of CFRP is considered and compared with the UD CFRP. The material properties of the woven CFRP is shown in Table 4.

***Table 4.** Material properties of woven CFRP*

Parameters	E_1 (GPa)	E_3 (Gpa)	G_{12} (Pa)	G_{13} (Pa)	G_{23} (GPa)	Nu_{12}	X^T	X^C	Y^T	Y^C	S^L	S^T
CFRP Woven	91.82	9	19.5	3	3	0.05	829	439	50	140	50	1

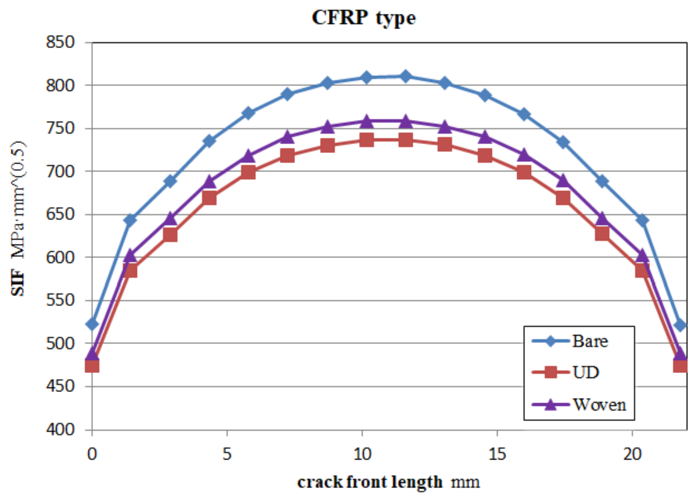


Fig. 7 *Comparison between the UD CFRP and Woven CFRP*

Fig. 7 illustrated that the woven CFRP performs good as well, even though the elastic modulus is less than half of the UD CFRP. The woven CFRP reinforcement decreases the SIFs around 7%, which may decrease the fatigue crack growth around 20 - 30%. Moreover, it may be more applicable than the UD in offshore industries.

4.2 Adhesive

Since the adhesive layer is regarded as the key layer of the reinforcement system, it is necessary to investigate the influence of adhesive's properties to the reinforcement. Besides the MBrace, this section chooses another adhesive which has a better mechanical property. The details of Araldite K630 are shown in Table 4.

Table 5. *Material properties of Araldite K630*

Parameters	E_a(GPa)	t_n, t_s, t (MPa)	K_{nn} (10^{13} N/mm^3)	K_{ss}, k_{tt} (10^{13} N/mm^3)	G_n (N/m)	G_s, G_t (N/m)
Adhesive	6.5	33	6.07	3.03	1000	1250

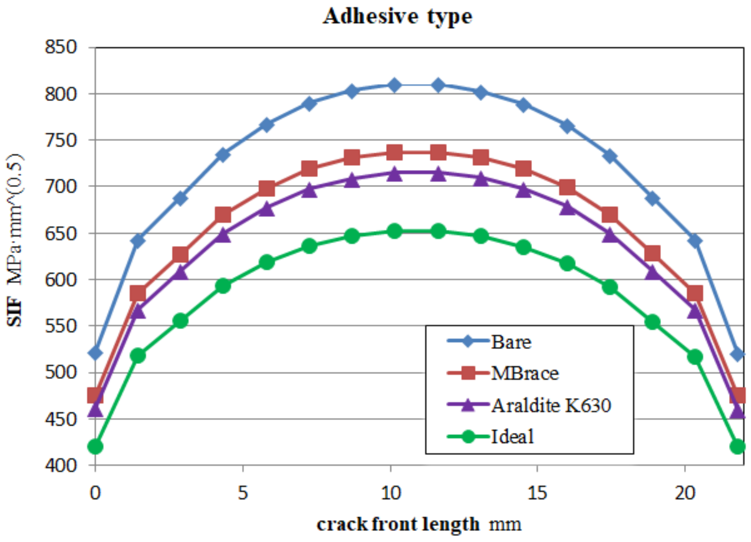


Fig. 8 *Comparison between different types of adhesive*

Fig. 8 shows that Araldite K630 prefroms better than the MBrace, decreasing around 12% of the SIFs, which may decrease about 40% of the crack growth rate. This section also considered a perfect bond condition (Ideal). The bond between the FRP and the pipe are bonded directly without the adhesive. In this case, the SIFs decrease about 20%, which could decrease the fatigue crack growth rate approximately 60%.

CONCLUSIONS

In this paper, the three-dimensional FE models of external surface crack growth in rigid pipe reinforced with CFRP are built. The SIFs along the surface crack front are calculated. The influences of CFRP type and adhesive type are discussed. The following conclusions can be summarized:

1) FRP reinforcement can decrease the SIFs along the surface crack growth in rigid pipe of different sizes of critical cracks.
2) UD CFRP and woven CFRP could both applied on offshore rigid pipes, considering the practical application, the woven CFRP may be more applicable.
3) As the key layer of the reinforcement system, the properties of adhesive have a significant influence on the reinforcement effect. Therefore it is important to improve the adhesive performance in order to obtain a better consequence as well as reducing cost.

Further research including the experimental validation, the crack-induced debonding mechanism, welding effect, etc. are under investigation. Those results will be reported in the future publications.

ACKNOWLEDGEMENTS

The China Scholarship Council (CSC) (201606950024) is gratefully acknowledged for funding the first author.

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