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Experimental study on repair of cracked pipe under internal pressure

Ali Abduljabbar[1], Haider Khazal[2], Abdul Kareem F. Hassan[3]
[1,2,3]Mechanical Department, Engineering college, University of Basrah, Iraq

ABSTRACT

Repair of cracked pipeline under internal pressure has been investigated in the present study. To this aim, an experimental test has been done on the cracked pipeline to find failure pressure. A longitudinal crack that cut 65% thickness of pipe has been applied on the external surface. Carbon fiber reinforced polymer has been used to repair the system. Additionally, a finite element model has been developed to estimate failure pressure of the unrepaired pipes. The results show that the failure pressure in unrepaired pipes is identical to the failure pressure predicted by the standards for corroded pipes, however, the failure pressure of repaired system is lower than the predicted results of standard for corroded pipelines.

Keywords: Cracked pipeline, CFRP, Failure pressure, Repair, Internal pressure

Corresponding Author:

Haider Khazal
Mechanical Department, University of Basrah
Basrah, Iraq

E-mail: haider.mehbes@uobasrah.edu.iq

1. Introduction

Steel pipelines are one of the most important equipment's to transfer water, sewage, and oil and gas product in all the world. Unfortunately, failure of pipes due to the crack or reduction in thickness are common modes of rupture in pipelines that can lead to economical or environmental problem and should be avoided by regular assessment. Three approaches of replacement of defected area, repair with metallic patch and repair with non-metallic patch can be employed for rehabilitation of pipeline according to the situation of pipeline and service condition [1]. Rehabilitation with carbon fiber reinforced polymers (CFRP), is growing as a versatile method [2-7]. Several numerical [8-12] and experimental [3, 13-15] studies have been done to demonstrate effectiveness of CFRP wrapping system for rehabilitation of pipes under internal pressure.

Generally, two types of defects are discussed in the literature. In the first type, a distributed defect due to the corrosion are detected on surface of pipeline. This type of defects are modelled as the reduction in thickness of pipe in the defected area [3, 4, 16, 17]. In the second type of defects, a crack is considered in the external or internal surface of the pipe, that is modelled as zero thickness defect (crack) [5, 6, 8, 9, 18].

In case of corroded pipes, ASME B31G [19] and ASME PCC-2 [20] proposed an analytical approach to find failure pressure of corroded pipes, and required repair thickness, respectively. A comprehensive comparison between different standards has been reviewed in [2]. Different type of metal loss in corroded pipes have been investigated in [4], and simplified analytical approaches were compared with a library of experimental tests. The results show a good correlation between two approaches. In reference [6], different dimension of defects have been numerically estimated and compared with the available experimental results, that shows a good agreement between numerical and experimental approaches. A comprehensive study can be found in the literature in case of distributed defect due to the corrosion, however, there are limited reports on cracked pipes.

Most of studies in cracked pipelines are numerical models like XFEM [6, 10, 21] or FEM [5, 7-9, 18, 22-24], that evaluate crack in pipes based on the fracture mechanics theory. [25-26] studied the temperature effect on cracked pressurized pipes. In contrast to the several numerical studies in cracked pipelines, there is no experimental study on cracked pipes under internal pressure. Consequently, in the present study an experimental procedure adopted to find failure pressure of steel pipes repaired by CFRP. The aim of this study is to evaluate the available analytical approaches in corroded pipelines in case of cracked pipes.

Accordingly, an experimental procedure to find failure pressure of repaired vessel is described in section 2. In section 3 a FEM model is employed to estimate failure pressure of the unrepaired pipe. Afterwards, results of experimental tests are discussed in section 4, and compared with standard relation for corroded pipelines in section 5. Finally, conclusions are briefly explained in section 6.

2. Experimental study

An experimental procedure was used to consider the effect of CFRP repair system on cracked pipeline under internal pressure. To this end, unrepaired pipe was numerically modelled to find the failure pressure test, and then, a repaired vessel by CFRP was tested under internal pressure up to the failure point. A Schematic view of cracked pipe has been shown in Figure 1. Internal pressure load was increased up to the rupture of the pipes. Comprehensive discussion on the material and test procedure is presented in this section.

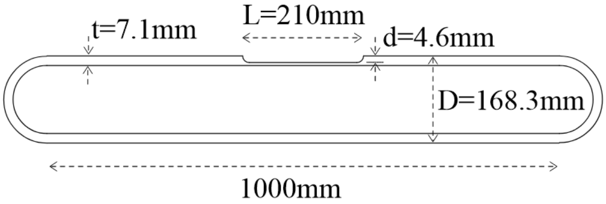


Figure 1. Schematic view of the cracked vessel

2.1. Pipe and defect

To do the tests, containers assembled from 1 m pipes and caps as depicted in Figure 2. Schedule 40 steel pipes with outer diameter 168.3 mm and 7.1 mm thickness, and endcaps with 10 mm thickness with full penetration groove welds were used, as depicted in Figure 3.

Figure 2. The vessels used for internal pressure tests

Figure 3. Details of end-cap and connection to the pipes

Seamless steel pipes ASTM A106 grade B were employed to construct vessels. A Stress-strain diagram of the steel extracted from the pipes has been depicted in

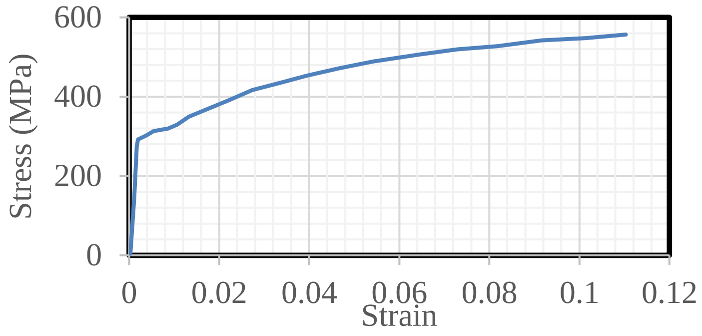


Figure *4*. As can be seen in this figure, yield and ultimate stresses of the pips is 300MPa.

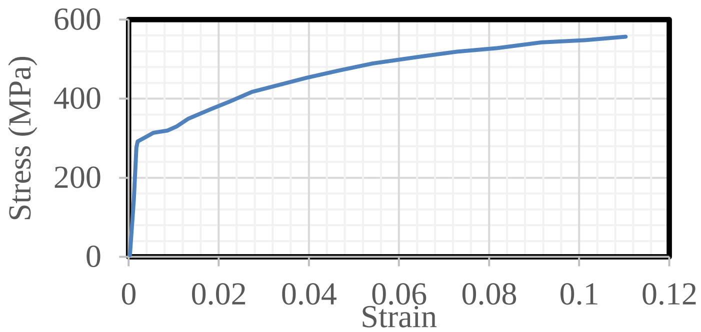


Figure 4. Stress-strain diagram of steel pipes

A crack with 210 mm length and 4.6 mm depth were applied in the centre of vessel in longitudinal direction as depicted in Figure 5. Accordingly, the remaining thickness of the pipe is 2.5 mm that is corresponding to the 35% of the initial thickness. The opening of the crack is 0.4 mm.

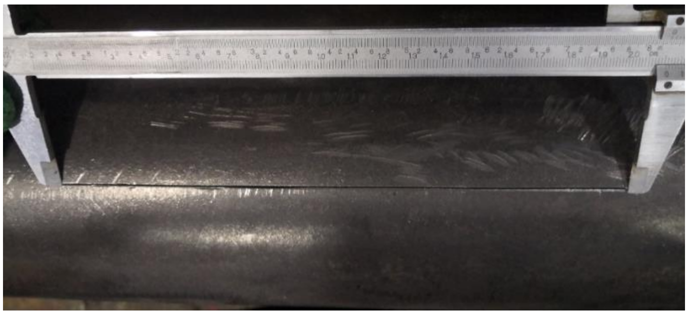


Figure 5. Longitudinal crack with 210mm length and 4.6mm depth considered as defect in central part of the vessel

2.2. Repair system

For repair system, woven fabric of CFRP were used. Totally 6 layer CFRP with 3 mm thickness and 500 mm width were considered to repair the pipe. The carbon fabric was impregnated with the epoxy resin (Figure 6), and then wrapped around the vessel (Figure 7). Material properties of carbon fibers are as described in Table 1. It should be noted that the surface of pipe roughened before wrapping the FRP. Due to the very thin width of the crack, no putty was used before applying the CFRP. However, sharp external corners of cracks were rounded to avoid cutting the CFRP during the test, and crack opening were filled with low viscosity epoxy polymer. Epoxy polymer was allowed to cure for 24 hours at room temperature after the repair process was completed before being tested.

Figure 6. Saturation of carbon fabric with epoxy resin

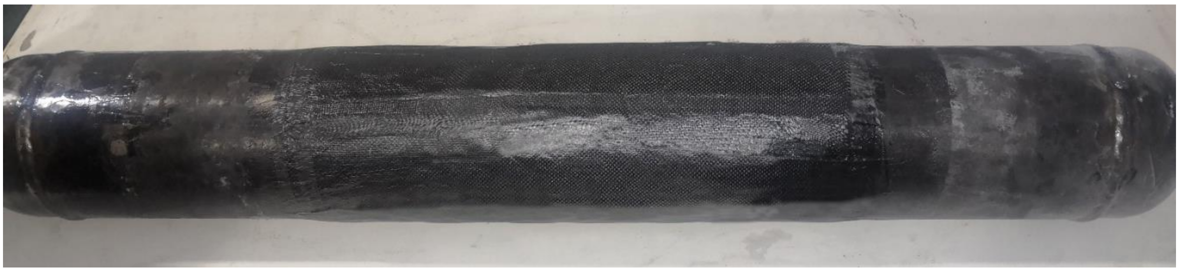


Figure 7. Repaired vessel with carbon epoxy

Table 1. Material properties of carbon fibers

Young’s Modulus			Poisson’s Ratio			Shear Modulus		
E_r	E_z	E_θ	υ_{rz}	$\upsilon_{r\theta}$	$\upsilon_{z\theta}$	G_{rz}	$G_{r\theta}$	$G_{z\theta}$
5.5GPa	23.4GPa	49GPa	0.43	0.196	0.43	0.69GPa	29.6GPa	0.69GPa

2.3. Internal pressure test

Figure 8 shows the setup that was used to do the internal pressure test. The Vessel filled with water, and after that, a hydraulic pump was used to apply internal pressure. The pressure increased up to the failure pressure.

Figure 8. Setup for doing internal pressure tests

3. Finite element modelling

A finite element model has been developed using ABAQUS to find the failure pressure of unrepaired pipe. Geometry and mesh configuration has been depicted in Figure 9, that show a refined mesh in cracked region. The geometry of the pipe was discretized using C3D8R elements, which denote an 8-node linear brick element with reduced integration formulation and hourglass control.

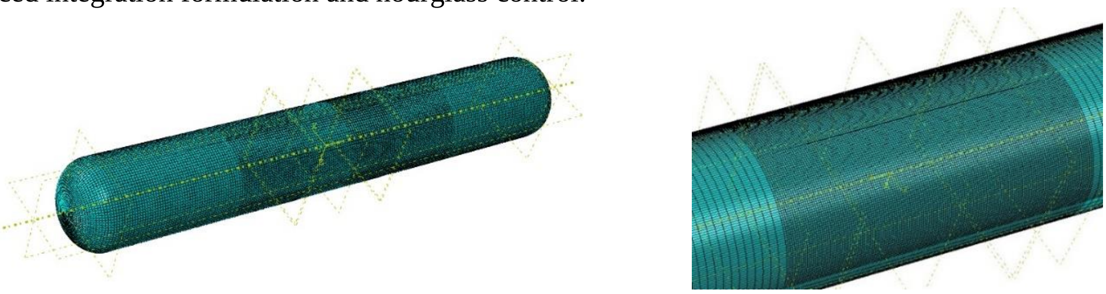
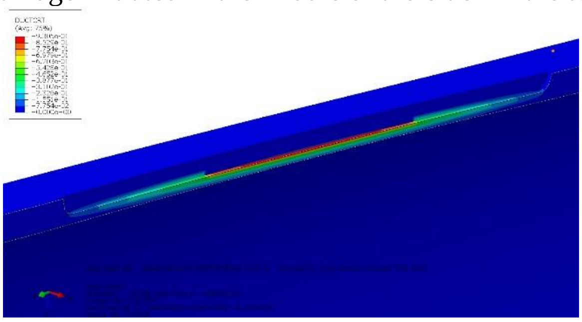


Figure 9. Geometry and mesh configuration of the unrepaired pipe

Nucleation, growth and coalesce of voids and micro-cracks are the main mechanisms of ductile damage in metallic materials when subjected to plastic strain. In order to simulate induced damage in the pipe during pressurization, the failure mode of pipe material is modelled according to the ductile damage criterion.
The internal pressure is applied to the internal surface of the pipe a, and pressure was raised from zero to 30 MPa, to determine the burst pressure of the pipe. The burst pressure was estimated when the failure of the pipe reaches based on defined failure criteria. The failure pressure estimate was discovered $15.2MPa$.
Figure 10 shows the damage propagation steps in the pressure in final end steps. As shown in this figure, the damage initiated in the middle of the crack in the top surface, and then propagated to reach the crack ends.



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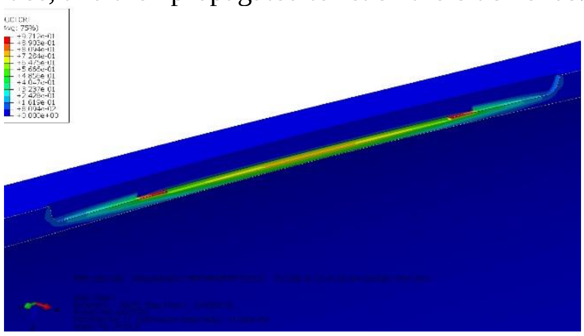

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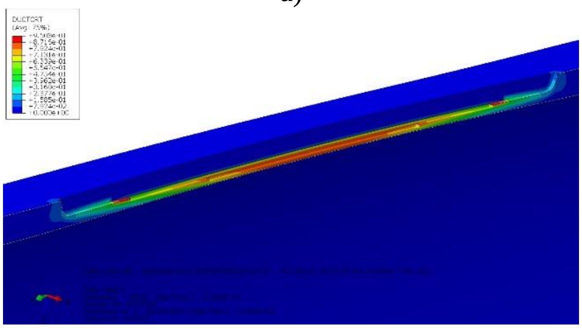

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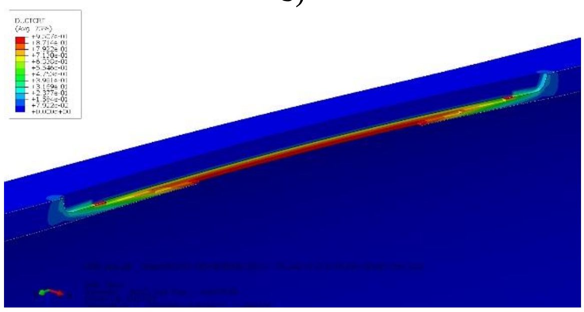

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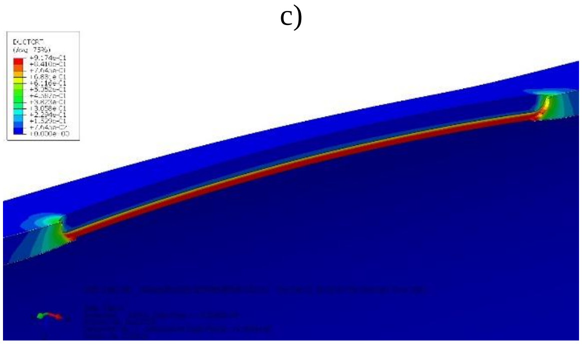

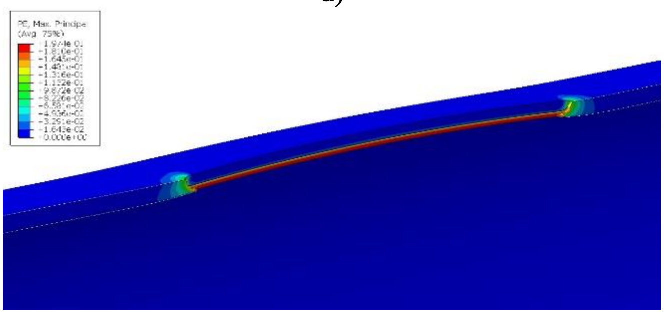

e) f)

Figure 10. The process of the pipe burst at different pressure

Figure 11 shows the deformation contour along the axis perpendicular to the pipe axis. According to this figure, the maximum value of deformation occurred in the middle of the pipe in cracked reign.

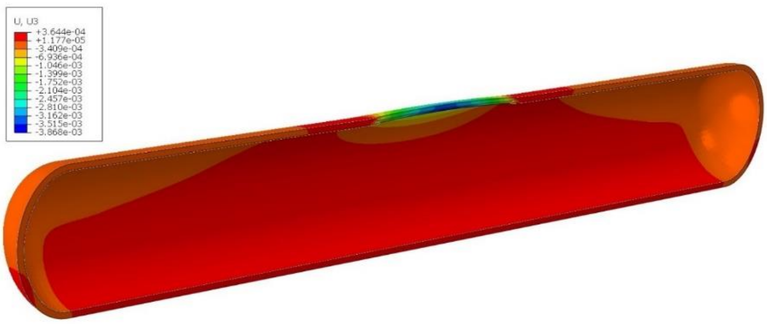

Figure 11. The contour of deformation in the pipe cross-section

In order to evaluation of stress distribution in the cracked area, the path of the pipe crack was defined. Figure 12 shows the defined path. In Figure 13 the diagram of von Mises stress distribution in the pipe is shown for three values of pressure. According to this diagram, the stress near the crack tip increases and reaches the maximum value in the middle of the crack until the failure pressure.

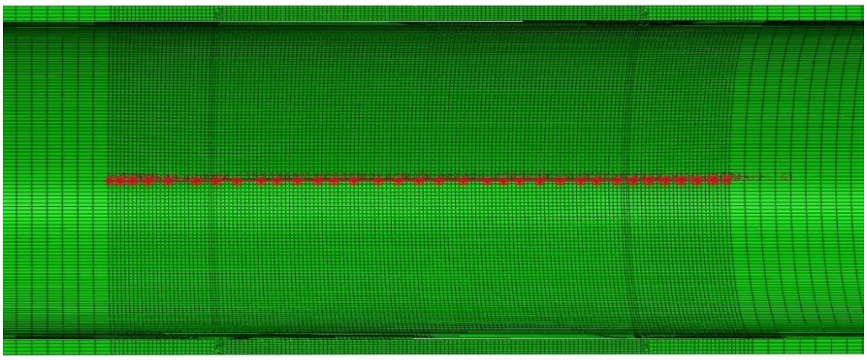

Figure 12. Defined path on pipe crack

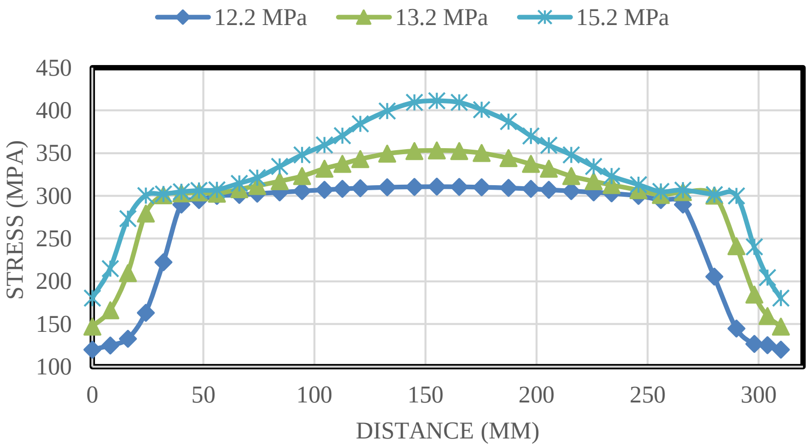

Figure 13. Von Mises stress distribution in pipe.

4. Results and discussion

As discussed in the previous section, internal pressure increased in the vessel up to the failure point. 255bar pressure was recorded during the test. Figure 14 shows the ruptured vessel after finishing the test. It is clear from this picture that the rupture occurred in carbon fibers, and additionally a delamination between pipe and CFRP is seen around the crack. Delamination around the crack is due to the high-water pressure injected between pipe and CFRP.

Figure 14. Situation of pipe after burst test

Figure 15 shows situation of crack after rupture. As can be seen in this figure, the crack length increased to 254 mm.

Figure 15. Crack propagation in steel pipe after rupture

To comparison the results with the standards, ASME B31G is used to predict the failure stress level. According to this standard, the failure stress can be calculated as equation (1) for $z = \frac{L^2}{Dt} \leq 20$ [19]

$$S_F = S_{flow}\left(\frac{1-\frac{2}{3}\left(\frac{d}{t}\right)}{1-\frac{\frac{2}{3}\left(\frac{d}{t}\right)}{M}}\right) \tag{1}$$

and for $z > 20$

$$S_F = S_{flow}\left(1-\frac{d}{t}\right) \tag{2}$$

where L, D, t and d are length of defect, diameter of pipe, thickness of pipes, and depth of flaw. Furthermore, S_{flow} and M is defined as

$$S_{flow} = 1.1SMYS \tag{3}$$

$$M = (1 + 0.8z)^{0.5} \tag{4}$$

$SMYS$ is specified minimum yield strength at ambient condition. Considering $L = 210mm,\ d = 4.6mm,\ D = 168.3$ and $SMYF = 300MPa$, they leads to the $z = 36.9$, and $S_{flow} = 330MPa$. Accordingly, the failure stress is calculated as $S_F = 116.2MPa$. Modified relation of B31G suggest the following relation for $z \le 50$

$$S_F = S_{flow}\left(\frac{1 - 0.85\left(\frac{d}{t}\right)}{1 - \frac{0.85\left(\frac{d}{t}\right)}{M}}\right) \tag{5}$$

where,

$$M = \left(1 + 0.6275z - 0.003375z^2\right)^{0.5} \tag{6}$$

Accordingly, the failure stress based on the modified relation is $S_F = 164.7MPa$. Computing failure stress, the failure pressure is calculated as

$$P_F = \frac{2S_F t}{D} \tag{7}$$

Estimated failure pressure based on original B31G and modified relation are $P_F = 9.8MPa$ and $P_F = 14.3MPa$, respectively. Based on the finite element modelling, failure pressure of 15.2 MPa has been estimated that has good agreement with modified B31G.

Based on the ASME standard, the required thickness of repair, t_{repair} to guarantee internal design pressure P with assuming that steel material is expected to be yield with elastic-perfectly plastic material is [20]

$$t_{reoair} = \frac{1}{\varepsilon_c E_c}\left(\frac{PD}{2} - st_s\right) \tag{8}$$

where $s = SMYS$ and t_s are specified minimum yield strength and minimum remaining wall thickness of the steel pipe, respectively. And E_c and ε_c are tensile modulus and allowable strain, respectively, of the composite in the circumferential direction. Assuming $t_{repair} = 3mm$, design pressure is calculated as $P = 29.5MPa$.

Failure pressure of the vessel with 3 mm composite thickness was obtained 25.5MPa according to the experimental test. Clearly, comparing experimental results for failure pressure and ASME for design pressure shows the recommended relation for composite repair in crack condition is not safe. It can be attributed to the stress concentration in crack condition that should be considered in strengthening of the cracked pipes.

2. Conclusions

In this study, the effect of non-metallic repair system like CFRP was considered on cracked pipeline. A finite element model was compared with prediction of ASME standard for failure pressure in unrepaired pipeline. Comparing original and modified version of failure stress of ASME B31G with FEM simulation shows better estimation of modified relation of ASME B31G.

To investigate the effect of CFRP repair system in cracked pipelines, an experimental test was done. To this end, a longitudinal crack applied on outer surface of pipes depth of 4.6 mm. Failure pressure of cracked pipeline was 25.5 MPa that is lower than the recommended values for design pressure based on the ASME. It shows that the recommended relations of standards for corroded pipelines cannot be used in case of cracked pipes.

The effect of crack length and depth have to be investigated in the further studies. Additionally, it is recommended to study the effect of CFRP on internal cracks caused by corrosive materials.

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Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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