Experimental study on radial interacting corrosion for X42 pipelines

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Abstract. The integrity of pipeline is compromised when corrosion develops. The corrosion referred to radial interacting corrosion which is happening internally and externally of pipeline wall at the same time. This paper investigates the effect of corrosion in the radial direction towards the failure burst pressure. Four types of corrosion defect arrangement were developed from literatures and tested experimentally to compare the failure burst pressure of the pipes with radial interacting corrosion and external corrosion. The external corrosion failure burst pressure was calculated theoretically by using Modified ASME B31G standard. The results of the failure burst pressure have shown that pipes having radial interacting corrosion fails at a lower burst pressure compared to the pipes having only external corrosion defect.

1. Introduction
Carbon steel is the most used material in the industry since 1930’s because it is economical, safe and has good mechanical properties [1]. Carbon steel pipe is constantly exposed and subjected to harsh environment, high pressure, high temperature and multiple hazards all of which depends on the location it is installed. There are numerous types of hazards and defects that could affect the pipeline and if left unchecked it could lead to failure. Failure is not an option because it has severe consequences on production, cost and environment. Due to this, hazards and defects has to be identified to ensure proper protection, prevention and it is fit for service [2]. The defects are also a concern because ageing pipeline or damaged pipeline is susceptible to the formation of corrosion and prone to accidents [3]. Corrosion is a threat because as the thickness of the wall becomes thinner, it will reduce the pipeline structural integrity and can lead to failure [4].

Corrosion in offshore pipeline is a common thing and it needs to be dealt with fast in order to reduce the risk of structural failure which may lead to unwanted consequences. According to [5], corrosion is bound to happen in the presence of an aqueous media which contains electrolyte, and this can result in an electrochemical reaction. There are two main forms of corrosion that occurs on the pipeline which are external and internal corrosion.

External corrosion as the name suggest happens externally on the pipe wall. Carbon steel pipe is susceptible to this kind of corrosion due to the constant exposure and harsh environment it is located in and some measures were taken to reduce the corrosion process which includes anticorrosion coating on the outer pipeline wall and also sacrificial anodes [6].

Internal corrosion is a type of corrosion that occurs in the pipeline. Pipeline is used to transfer fluid from the wells and ultimately to the processing facilities. However, corrosion is inevitable because the fluid can contribute to the forming of corrosion due to the reactivity of the fluids carried [5]. Chemical contents in the fluid will also contribute to a certain type of corrosion called sweet corrosion and sour
corrosion and is caused by the carbon dioxide and sulphur content. To reduce the occurrence of internal corrosion, the commonly used method is by applying corrosion inhibitor.

![Figure 1](image)

**Figure 1.** Corrosion defect spacing in longitudinal and circumferential orientation [1].

Corrosion defects can occur on the pipeline wall either as an isolated corrosion or interacting corrosion. The parameter that differentiates the two are the spacing between the defects. Isolated corrosion is a type of corrosion that does not interact with the surrounding corrosion and act as a single corrosion. Interacting corrosion on the other hand is a type of corrosion that interacts with the surrounding corrosion defect provided it satisfies the required spacing. Isolated and interacting corrosion both is a threat to the pipeline integrity however, the more severe one is the interacting corrosion as it will cause a much lower failure pressure to the pipeline compared to the isolated corrosion effect [7]. This is due to the interaction of the adjacent defects occurring at the pipeline wall.

Interacting corrosion is composed of interactions occurring at two different orientations mainly, longitudinal and circumferential orientation. The spacing of the defect between one another plays a vital role in determining whether the corrosion is isolated or interacting as the further the spacing, the lower the possibility of interaction. Based on the study conducted by [8], X60 pipe of circular shaped defect in longitudinal and also circumferential orientation of the same parameter was tested. It was shown that, longitudinal orientation interaction can occur to up to 3t distances and circumferential orientation only occur up to less than 1t. This shows that spacing distance differ depending on the orientation of the defect. Both orientations have its own formula in order to calculate the spacing required for it to interact with one another.

Commonly, corrosion defects that are closely spaced in a colony would have a smaller failure pressure compared to an isolated defect which is mainly caused by the interaction of adjacent defect with one another [7]. Numerous studies have been conducted on the defects occurring either externally or internally, however, there has yet to be a clear guidance on the radial direction which involves both internal and external defect occurring simultaneously on the pipeline wall.

Numerous researches have been conducted in the past years on corroded pipelines which includes the failure mechanisms and failure assessments [9]. The research is usually conducted experimentally and also by using finite element analysis. Codes and guidelines were developed by the researchers to evaluate the residual strength of the corroded pipeline and it is mostly in empirical formula based on the results from experiments and numerical analysis conducted [10]. The most commonly used codes in the industry is ASME B31G [11]. There are other codes that are also used such as Modified ASME B31G and DNV RP F101. For example, DNV RP F101 has a specific code for single defects, interacting defects and complex defects as defect types behaves differently [12]. However, pipe operators around the globe are free to choose which to apply as there is no universally used codes and guidelines agreed up until now [13].
Experimental of the pipelines containing defects has been conducted in the past in order to develop equations and to evaluate the burst pressure of the pipe when subjected to corrosion defects. In the beginning, burst pressure of the pipelines is only subjected to isolated defects and as time progresses interacting defects are also included [14]. Finite element analysis was introduced as an alternative to experimentation and it can be used to study the failure behavior of pipelines as it is a powerful tool [15]. Currently, the results of the past burst pressure test that has been published is compared to the experiments and/or finite element analysis result that was conducted to determine the accuracy of the equations developed to enhance the evaluation of the remaining strength of the pipeline which will ensure the safety of the pipeline [16].

At present, the remaining strength of a corroded pipeline is usually determined by using the recommendations, practices and design codes developed in the published studies conducted. However, the recommended practices and design codes do not take into consideration of the corrosion interactions that occurs in the radial direction which is defects occurring simultaneously in the internal and external pipeline wall. Hence, this research was carried out to find the failure burst pressure when corrosion defects occur simultaneously on the internal and external sides of the pipeline wall experimentally and compare it to a Modified ASME B31G theoretical failure burst pressure of pipe having only external corrosion. The result was used to determine the pipeline remaining strength and ensuring it is fit-for-purpose. This paper is aiming to examine the burst pressure capacity of the pipe with the selected of the radial interacting defect arrangements.

2. Physical experiment
Numerous researches have been done in the late 1970’s to address the remaining failure pressure of the pipe which was caused by metal loss of the pipeline wall as stated by [1]. Database were developed based on the experiments and finite element analysis conducted. Selection of corrosion combinations is retrieved from past research papers and implemented in this research. The defects will be made internally and externally according to the combinations. Based on [15], the following clustering of defects were developed, as tabulated in Table 1.

| Table 1. Interacting corrosion orientation. |
|---------------------------------------------|
| No | Experimental | |
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |

| No | External Corrosion | Internal Corrosion |
|---|-------------------|--------------------|
| 1 | ![Image](image1.png) | ![Image](image2.png) |
| 2 | ![Image](image3.png) | ![Image](image4.png) |
| 3 | ![Image](image5.png) | ![Image](image6.png) |
| 4 | ![Image](image7.png) | ![Image](image8.png) |
2.1. Defect shape
Circular defect shape has been chosen due to the ease of creating the artificial corrosion [4].

2.2. Defect arrangement
Defect arrangement has been selected and chosen which includes single, pair and multiple interacting corrosion [1]. Internal corrosion defect is a challenge to produce and is restricted to the machine limitation that produces the artificial corrosion at UTP, Block 16.

2.3. Thickness of wall, \( t \)
Thickness of wall was chosen as 6 mm and later thickness was modified into 3 mm because it due to the limitations of the equipment used in the lab.

2.4 Width of defect, \( c \)
Width of the defect beyond the range of 0.0785D has small effect on burst pressure [4]. Width of defect is 16.8 mm (0.15D).

2.5 Length of defect, \( l \)
Length of defect considered is less than 1.5D as effect on burst pressure is negligible when it is above that value [4]. Hence, the defect length chosen is 33.6 mm (0.3D) for all defect.

2.6 Longitudinal direction
Spacing should be less than or equals to 3t for defect to interact [8]. Hence, spacing is 3 mm (0.5t)

2.7 Circumferential direction
Spacing should be less than 1t for defect to interact [8]. Hence, spacing is 3 mm (0.5t)

![Image of defect shape and spacings](image_url)

**Figure 2.** Colonies of defect and the spacings between them (Adapted from [15]).

![Image of pipe samples with corrosion defect](image_url)

**Figure 3.** Pipe samples with corrosion defect.
3. Results and discussion

3.1. Theoretical failure burst pressure
The theoretical failure burst pressure of the 6 mm and 3 mm pipe specimen was calculated by referring to the ASME B31G, Modified B31G level 1 evaluation, DNV (Part A) and DNV (Part B) assessment for interacting defects. The theoretical failure burst pressure takes into account only the external corrosion in the pipe specimen. The theoretical failure burst pressure were used to validate the experimental values of the failure burst pressure of the pipe.

Table 2. Result summary of 6 mm specimen.

| Defect Type | ASME B31G (MPa) | Modified B31G (MPa) | DNV (A) (MPa) | DNV (B) (MPa) |
|-------------|----------------|-------------------|--------------|--------------|
| 1           | 39.77          | 40.37             | 31.86        | 41.38        |
| 2           | 36.56          | 37.09             | 28.99        | 37.65        |
| 3           | 39.36          | 39.94             | 31.86        | 41.38        |
| 4           | 36.56          | 37.09             | 28.99        | 37.65        |

Referring to Modified B31G, the values from the theoretical calculations can be seen in Table 2 above and the lowest failure burst pressure were 37.40 MPa with the highest at 40.37 MPa. The highest failure burst pressure was due to the single corrosion defect and the lowest having interacting defect in the longitudinal direction.

Referring to Modified B31G, the values from the theoretical calculations can be seen in Table 3 above and the lowest failure burst pressure were 18.80 MPa with the highest at 18.06 MPa. The highest failure burst pressure was due to the single corrosion defect and the lowest having interacting defect in the longitudinal direction.
Table 3. Result summary of 3 mm specimen.

| Defect Type | ASME B31G (MPa) | Modified B31G (MPa) | DNV (A) (MPa) | DNV (B) (MPa) |
|-------------|----------------|--------------------|---------------|---------------|
| 1           | 19.56          | 18.91              | 15.41         | 20.02         |
| 2           | 18.22          | 18.05              | 13.53         | 17.57         |
| 3           | 19.37          | 18.80              | 15.41         | 20.02         |
| 4           | 18.22          | 18.06              | 13.53         | 17.57         |

3.2. Burst pressure
The first experiment conducted uses API X42 pipe with 6 mm thickness and type 1 defect. The pipe was prepared and set up into the burst rig to conduct the experiment. The experiment was conducted and the pipe did not burst. It has only achieved a maximum pressure of 42.47 MPa. The experiment was stopped due to the maximum pressure the equipment can cater which was 45 MPa. Leakage was present in the 40 MPa range during the experiment. Leakage was due to the design of the burst rig itself. The pipe should burst based on theoretical calculations. However, it did not burst because theoretical calculations only take into account the ideal conditions for the pipe and its surrounding. The pipe specimen thickness was more than 6 mm due to the tolerance by the manufacturer and the defect depth, width also varies due to human error. This was reduced by fabricating the defect at a specialist center but it is unavoidable.

A second experiment was conducted using another pipe specimen. The experiment was conducted to verify whether the pipe specimen with the most severe corrosion defect can burst using the same equipment. This is to verify that the specimen was suitable for the equipment available in the lab. The second experiment was conducted using an API X42 pipe with 6 mm thickness and type 4 defect which was the most severe defect type compared to the other pipe specimen. The experiment was conducted and the pipe failed to burst achieving a maximum pressure of 44.93 MPa. The reasons for the failure was similar to the first experiment which was due to the maximum pressure the equipment can withstand, leakage due to design of burst rig.

A solution for this setback was developed and it was decided that the pipe needs to be sent back to the specialist. Modification to the remaining specimen was needed. The modification includes thinning of the wall thickness from 6 mm to 3 mm. The modification of the specimens was sent to the same fabricator and they managed to modify the pipe, however, pipe specimen type 1 was accidently punctured due to poor workmanship by the fabricator which resulted in a defective specimen.

The third experiment was done on a 3 mm pipe specimen with a type 2 defect. The specimen was subjected to a maximum of 18.58 MPa of pressure before the pipe specimen burst. The pipe specimen manages to burst. However, the result was not as expected as the failure burst pressure was higher when compared to the theoretical calculations with only external defect. This was due to the poor workmanship of the fabricator in which the artificial corrosion depth and thickness does not follow the specifications.

The fourth experiment was done on a 3 mm pipe specimen with a type 3 defect. The specimen was subjected to a maximum of 17.79 MPa of pressure before the pipe specimen burst. The pipe specimen manages to burst. The result as shown in Figure 6 was as expected as the failure burst pressure was lower when compared to the theoretical calculations with only external defect. This was due to the improved workmanship of the fabricator in which the pipe conforms to the requirements of the specifications.

The fifth experiment was done on a 3 mm pipe specimen with a type 4 defect. The specimen was subjected to a maximum of 13.57 MPa of pressure before the pipe specimen burst. The pipe specimen manages to burst. The result was as expected as the failure burst pressure was lower when compared to the theoretical calculations with only external defect. This was due to the improved workmanship of the fabricator in which the pipe conforms to the requirements of the specifications.
The experiment was a success as all pipe specimen managed to burst with a lower failure burst pressure than the theoretical failure burst pressure due to the existence of radial corrosion defect. However, type 2 pipe has obtained a failure burst pressure higher than the theoretical burst pressure due to the human error made by the manufacturer which includes a punctured hole in pipe specimen type 1 which made it defective and cannot be tested in the experiment.

![Figure 5. Result of 3 mm specimen with type 2 defect.](image)

![Figure 6. Result of 3 mm specimen with type 3 defect.](image)
Figure 7. Result of 3 mm specimen with type 4 defect.

Table 4. Result summary of 6 mm specimen.

| Defect Type | Modified B31G (MPa) | Experimental (MPa) | Comment       |
|-------------|---------------------|--------------------|---------------|
| 1           | 40.37               | 42.47              | Did not burst |
| 2           | 37.09               | -                  | -             |
| 3           | 39.94               | -                  | -             |
| 4           | 37.09               | 44.93              | Did not burst |

Table 5. Result summary of 3 mm specimen.

| Defect Type | Modified B31G (MPa) | Experimental (MPa) | Comment                         |
|-------------|---------------------|--------------------|---------------------------------|
| 1           | 18.91               | -                  | Pipe punctured during fabrication|
| 2           | 18.05               | 18.58              | Water leakage during experiment |
| 3           | 18.80               | 17.79              | -                               |
| 4           | 18.06               | 13.57              | -                               |

4. Conclusion
It has been shown that there were numerous researches conducted to study the effects of corrosion on pipelines internally and externally. The studies conducted has been mainly focusing on isolated corrosion and interacting corrosion occurring on pipelines. The development of interaction rules and assessment has mainly been used to evaluate the severity of defects and to get the remaining strength of the pipe to ensure it is fit for purpose. However, interaction in the radial direction has not been covered. Hence, this research is conducted to cater for that gap and to provide an insight to the effects of radial interaction on the strength of the pipeline. The outcome of this paper has proved that radial interacting corrosion does affect the pipeline integrity and failure burst pressure by having a lower experimental failure burst pressure when compared to the theoretical failure burst pressure of pipe specimen having only external corrosion defect.
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