# TECHNICAL NOTE

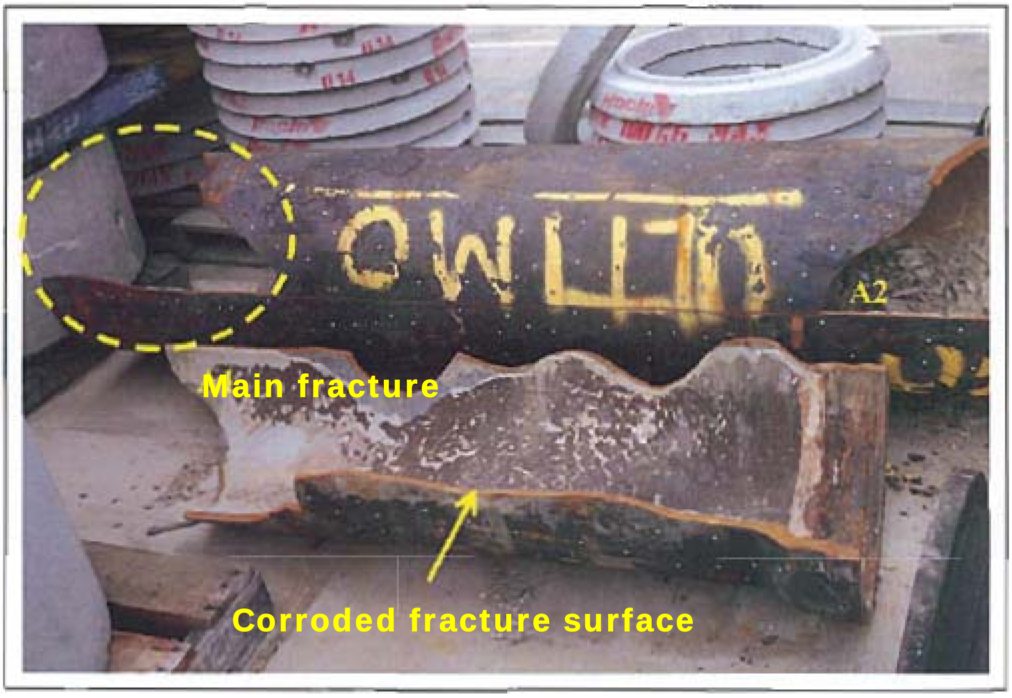
Monash University
Clayton Campus
Melbourne
Tel: +61 (0)399054963
http://www.criticalpipes.com/

| | | | | |
|---|---|---|---|---|
| Project: | Advanced Condition Assessment & Pipe Failure Prediction Project (ACAPFP) | | | |
| Title: | Review on Harris Street/Ultimo Lane Water Main Failure | | | |
| Ref.: | Monash-ACAPFP-Activity1-TN1 | Date: | 22/01/2014 | Page 1 of 21 |
| Rev.: | 01 | By: | D.J.Robert (Monash), J.Kodikara (Monash) and J. Rajalingam (Sydney Water) | |

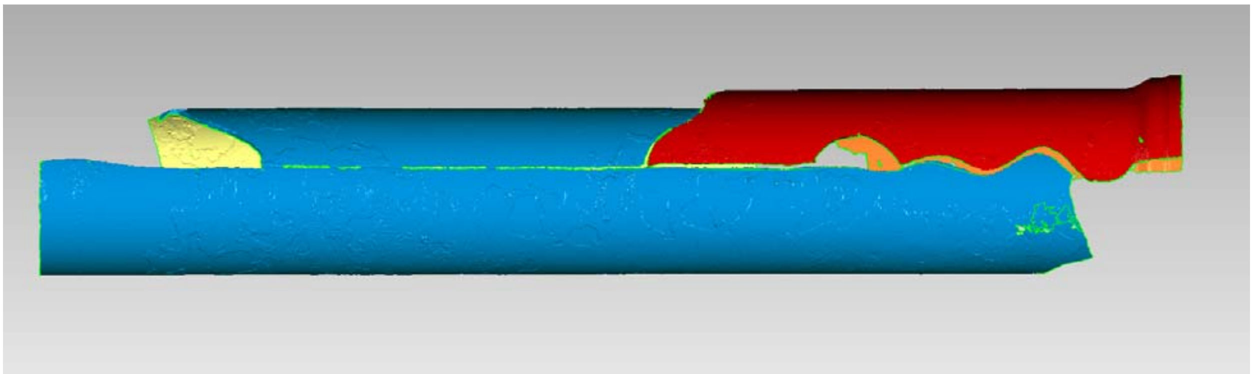
## 1 INTRODUCTION

### 1.1 WATER MAIN FAILURE

This report provides a preliminary evaluation of the pipe failure at the intersection of Harris Street and Ultimo Lane that took place at 11.05pm on the 10th of August, 2013. The failure occurred in a 500mm diameter cement lined spun cast pipe laid in 1961 (Figure 1-1). The road surface was a bitumen covered concrete surface (250 mm thick), and the pipe burial depth to the pipe crown was about 1.6m. Figure 1-2 shows some pictures indicating the location and some consequences of the failure. Herein, this failure is referred to as “Harris/Ultimo pipe failure”. As part of Activity 1 of Advanced Condition Assessment and Pipe Failure Prediction (ACAPFP) Project, a study has been undertaken to investigate the drivers of failure; thus to put forward an explanation (a hypothesis) on how the failure may have eventuated.



**(a) Water main viewed on 22nd Oct 2013 (Ref. [**Error! Reference source not found.**])**



**(b) Scanned image of the main using 3-D scanner (Ref. [**Error! Reference source not found.**] with the curtsey of University of Technology Sydney (UTS), ACAPFP Partner)**

**Figure 1-1 Pictures of the failed water main**

(a) Failure site (Ref. [6]) (b) Water flooding to adjacent streets (Ref. [4])

**Figure 1-2 Damage induced by the water main failure**

## 1.2 OBJECTIVE

The objective of this technical note is to provide an explanation to the water main failure occurred at Sydney on 10th August 2013. Numerical investigations were performed for this purpose on the basis of the data sheet provided for this case study (Ref. [7,8]).

# 2 INPUT DATA

The following information was used in this analysis:

- Data reported in Failure datasheet provided by SW (Ref.[7,8]);
- Photographs taken at the site of pipe failure (Ref.[7,8]);
- Data gathered during visits (by J Kodikara with J Rajalingam) to Potts Hill facility where failed pipe sections were stored;
- 3D laser scanning undertaken by UTS (Ref. [5]);
- Data gathered during visit by J Kodikara to Pipe failure site after the failure has been reinstated; and
- Metallurgist’s report provided by SW (Ref. [9]).

All the input data used in the numerical simulations are either based on the information gathered above for this case study or based on assumptions, in which case, they are specifically noted.

## 2.1 PIPE LAYOUT

The layout of the failed water main is shown in Figure 2-1 along with the adjacent pipes. It appears that there were 2 more pipes laid adjacent the failed pipe (D500). A pipeline of diameter 750mm was laid above the failed pipeline (with a gap of more than 100mm between the failed pipe and D750 pipe, Ref. [8]) and another pipeline of D300 was connected to D500 pipeline as shown in Figure 2-1.

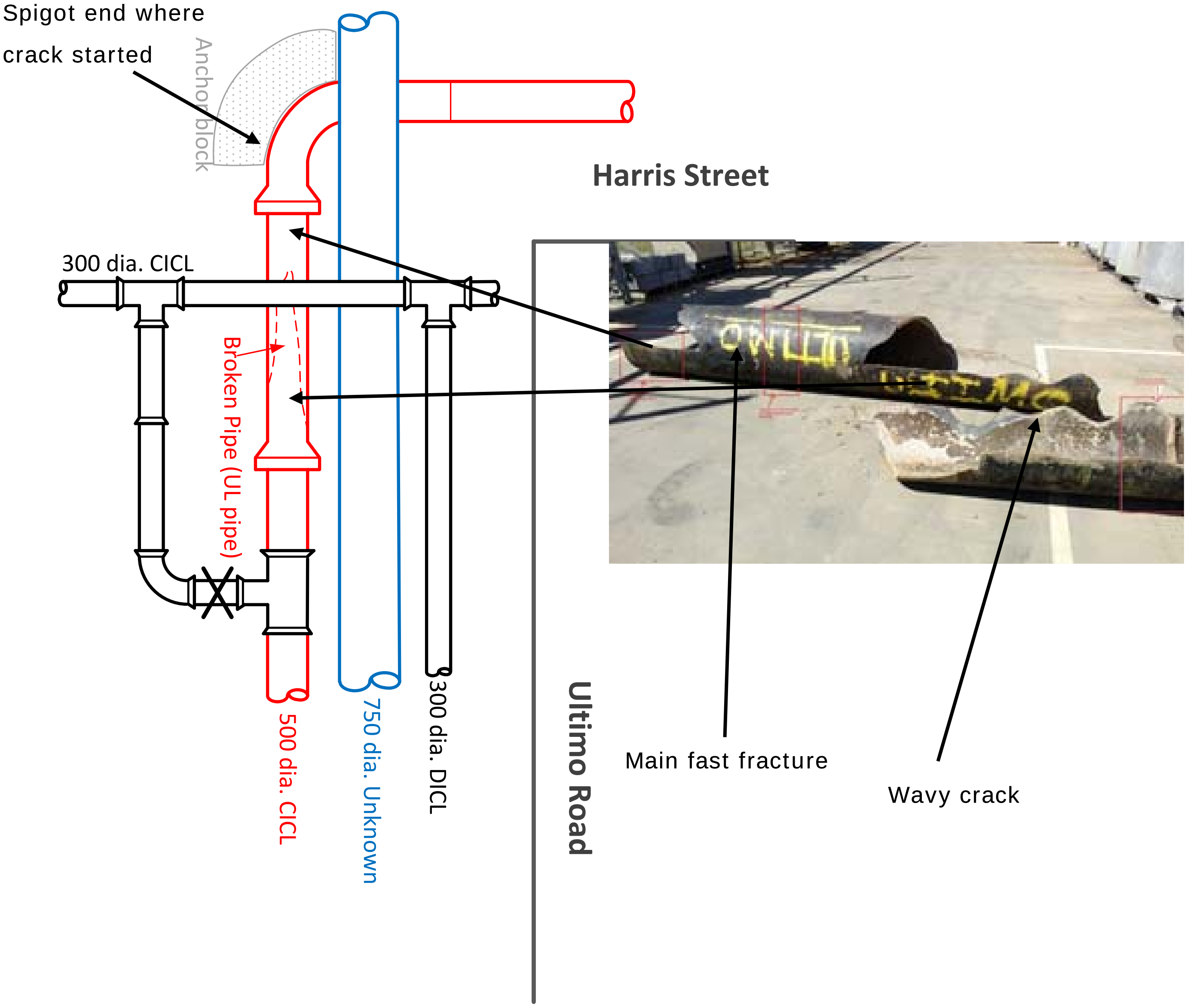


**Figure 2-1 Pipe layout of the failed pipes along with connections and other adjacent pipes (Modified from Ref. [7])**

## 2.2 PIPE DIMENSIONS

Dimensions of the pipelines are given in Table 2-1 on the basis of Ref. [8]. It should be noted that the thicknesses of D750 and D300 pipes are assumed based on previous pipe lay information.

| Pipeline | Diameter (mm) | Thickness (mm) |
|---|---|---|
| D500[1] | 500 | 16 |
| D750 | 750 | 30[2] |
| D300 | 300 | 12[2] |
| Note: 1 The gap between D500 and D750 is 150mm (Ref. [8])<br>2 Assumed pipe thicknesses | | |

**Table 2-1 Pipeline dimensions (Ref. [8])**

The dimensions of the bell used (see Figure 2-2) in the analyses are based on measured dimensions of a bell joint of a pipe section retrieved from Sydney Water test bed pipeline. Accordingly, the straight pipe (i.e. UL pipe shown in Figure 2-1) has a length of 175mm into the bell pipe as shown in Figure 2-2.

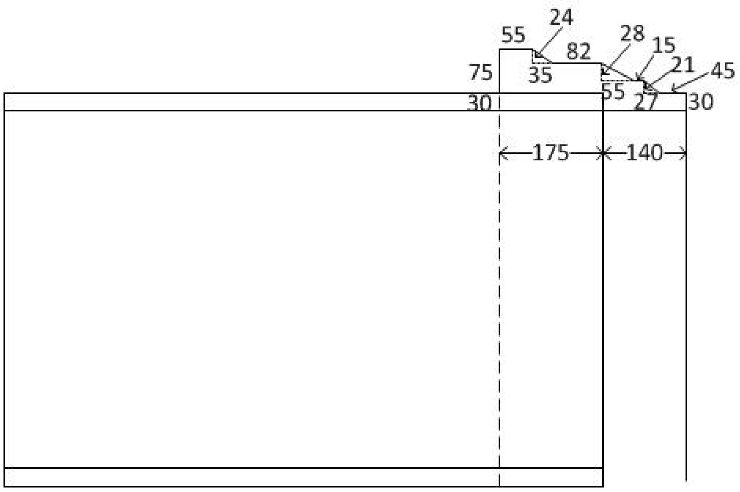


**Figure 2-2 Assumed dimensions (in mm's) of the bell**

## 2.3 CAST IRON PROPERTIES

The properties of the cast iron assumed in the numerical assessments are given in Table 2-2. These properties are based on the tests undertaken at Monash on the SW Test Bed pipe. Actual properties of the failed pipe are being measured using the failed pipe pieces made available by Sydney Water. An update of this case study using actual cast iron properties will be conducted in due course.

| Property | Unit | Description |
|---|---|---|
| Stiffness | GPa | 100 |
| Poisson’s Ratio | - | 0.3 |
| Density | $Kg/m^3$ | 7800 |
| Tensile strength | MPa | 100 |

**Table 2-2 Assumed cast iron properties**

## 2.4 ASPHALT AND SUBGRADE PROPERTIES

The details of the pavement and subgrade are summarised in Table 2-3.

| Property | Unit | Description |
|---|---|---|
| Pavement Details (Concrete + Bitumen) | | |
| Thickness | mm | 250 (Ref. [8]) |
| Stiffness | MPa | 3000 |
| Density | $KN/m^3$ | 23 |
| Poisson’s ratio | - | 0.3 |
| Subgrade properties | | |
| Thickness[1] | mm | 1350 (Ref. [8]) |
| Stiffness | MPa | 50 |
| Density | $KN/m^3$ | 19.5 |
| Poisson’s ratio | - | 0.3 |
| Note: 1 Thickness of the subgrade is obtained using pipe buried depth given in (Ref. [8]) and thickness of the pavement layer. | | |

**Table 2-3 Asphalt and subgrade properties**

## 2.5 TRAFFIC DATA

Typical traffic loads are obtained from Austroads (Ref. [3]) guidelines for single axle single tyre truck type configuration (SAST). An axle group load of 40kN was assumed for all the assessments considering a medium truck load.

## 2.6 OPERATING PRESSURES

On the basis of pressure measurements undertaken (Figure 2-3, Ref. [7])), the maximum operating pressure of D500 is around 550kPa (including static and water hammer). It should be noted that any horizontal thrust applied on the D500 pipe due to water velocity in elbow configuration is neglected in this regard.

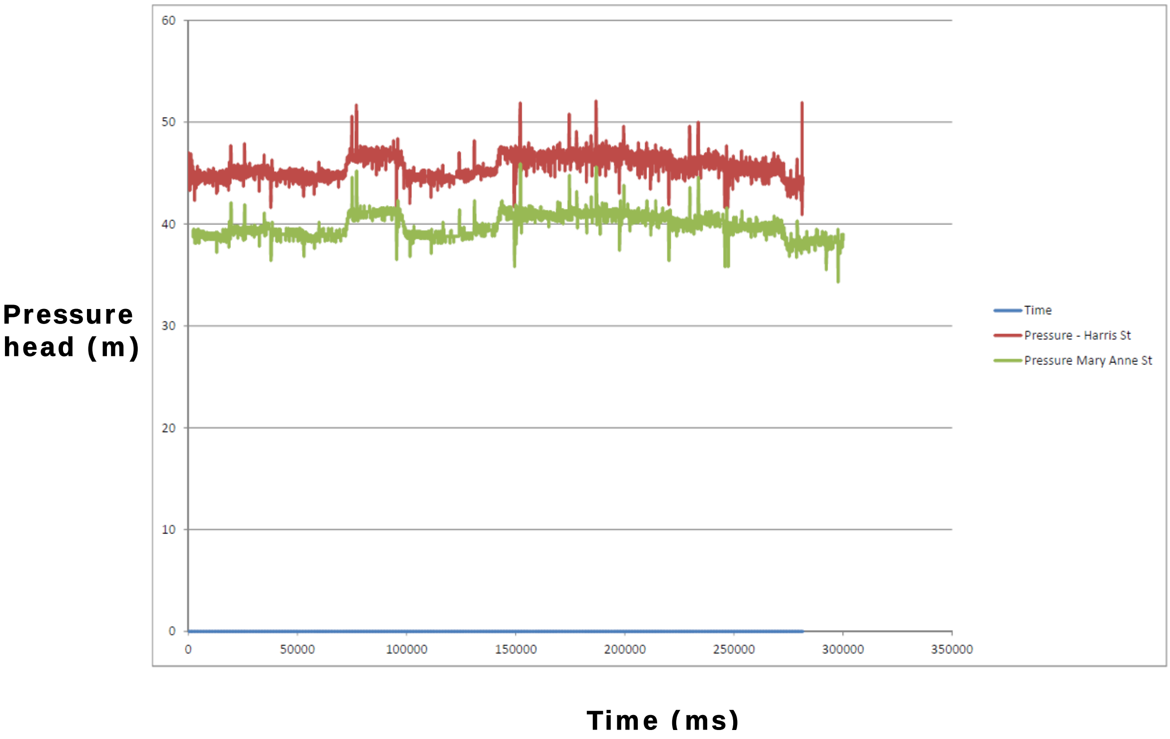


**Figure 2-3 Measured operating pressures of the D500 pipes after the event (Ref. [7])**

# 3 METALLURGICAL OBSERVATIONS

Metallurgical investigations were reported by John L Gray Pty Ltd (Ref. [9]) on 22nd Nov 2013 on the basis of the failed water main (Figure 2-1) using high powered metallurgical microscopes (1000X magnifications). According to the observations, only minimal amount of corrosion was appeared in the pipe except at the fracture. The observations summarised that there had been an older pre-existing crack at the socket and spigot connection and the failure could have initiated through such crack. The report further pointed out that the pre-existing crack could have significantly increased the likelihood of the failure.

# 4 FE ANALYSES

## 4.1 MODEL DESCRIPTION AND IDEALISATION

Three dimensional (3D) finite element analyses were carried out using ABAQUS 6.12 (Ref. [1]) to obtain the pipe stress conditions in current investigations. The pipes as well as the soil were represented by 8-noded brick reduced integration elements and the behaviour of both pipe and soil were assumed to be linear elastic. The soil side boundaries of the FE model were assumed to be smooth and are located far (i.e., 5m) from the pipe (& traffic loads) to eliminate any boundary effects. Figure 4-1 shows the mesh discretization (158,000 3-D elements to represent the soil and 220,000 3-D elements to represent the D500 pipe) and model dimensions. The appropriate dimensions and the mesh density of the model were selected after a number of trials to minimise mesh and boundary effects on the calculated pipeline stresses. It is to be noted that the element size around the area of the crack is selected as 1mm (this is based on an outcome from a separate study). The interaction between pipe and soil was modelled using Coulomb frictional model with a coefficient of friction of 0.5.

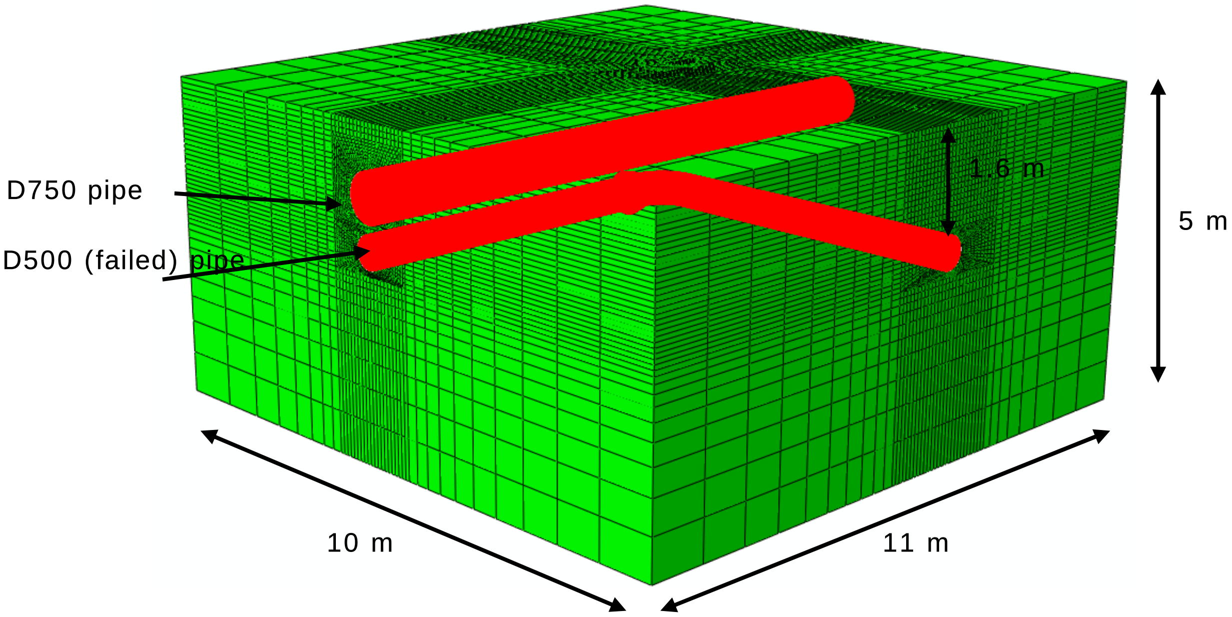


**Figure 4-1 FE model idealisation and mesh discretisation**

## 4.2 ANALYSES PLAN

Due to the complexity of the case, several analyses were conducted to explain the possible failure mechanisms of D500 pipeline. Firstly, analyses were performed to investigate the stress conditions of D500 pipeline under operation, assuming that there were no pre-existing cracks. Such analyses are useful to obtain the pipeline stresses in normal operational circumstances (i.e. nominal stresses). Analyses were also performed to examine whether there were any effects from the over-laid D750 pipeline on the D500 pipeline. Further analyses were conducted to investigate the influence of the presence of anchor block to restrain bell movements. Finally, investigations were performed to investigate the effects of pre-existing crack on the D500 pipeline. Table 4-1 presents a summary of the analyses undertaken.

| Objective | Analyses description | No of Analyses |
|---|---|---|
| Investigate the stress condition of D500 pipeline in normal operation (without pre-existing cracks) | Analysis on the case when no pre-existing cracks in D500 pipeline; with and without bell joint | 2 |
| Investigate the effects of over-laid D750 pipeline on D500 pipeline | Only D500 pipes with joint (Assuming no D750 pipeline running above) | 1 |
| | Operating D750 pipeline with higher pressures | 2 |
| Investigate the presence of an anchor block to restrain bell movements | An anchor block is introduced into the model having no crack, and to the model having crack length of 323mm | 2 |
| Investigate the presence of pre-existing crack on D500 pipeline | Change in the length of pre-exiting crack at 50mm, 150mm, 175mm, 225mm, 275mm, 325mm and 375mm | 7 |

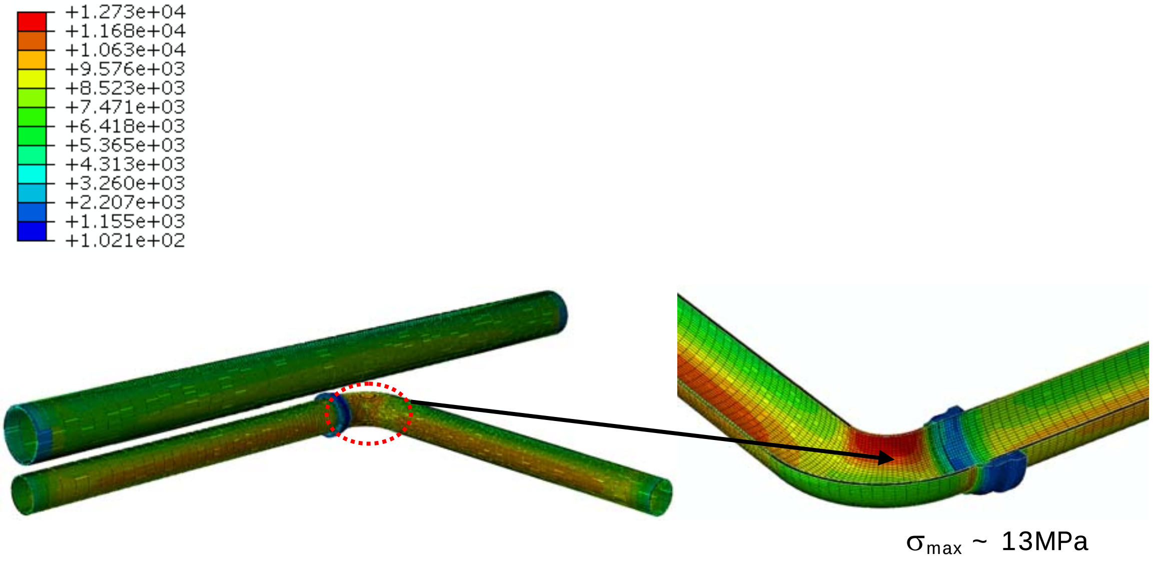
**Table 4-1 FE analyses plan**

## 4.3 RESULTS

The results of all the analyses undertaken are presented in this section.

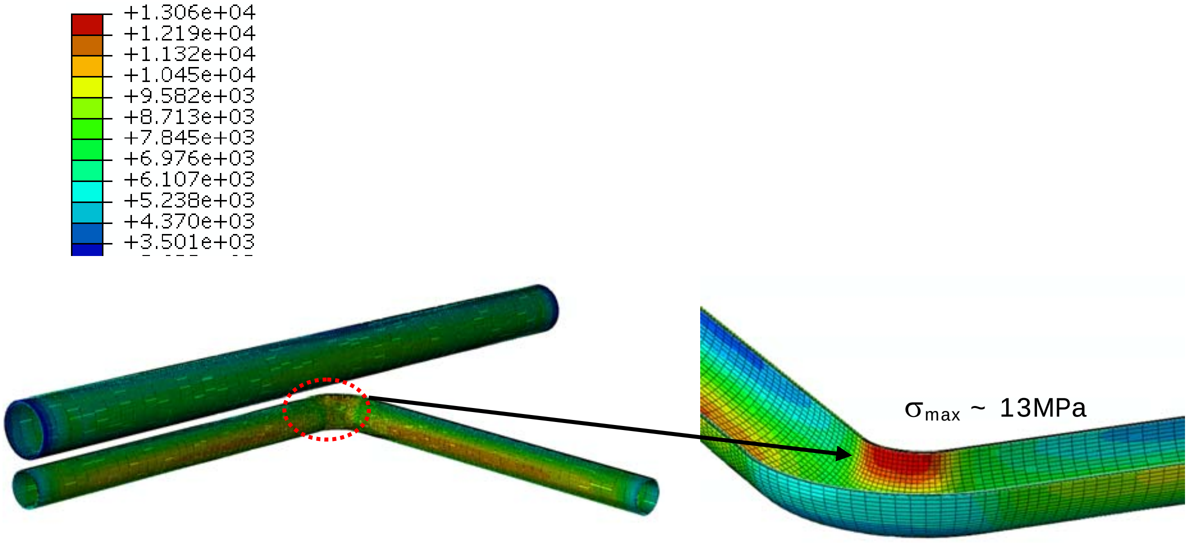
### 4.3.1 Normal operating scenario (without any cracks in the pipe)

First, analyses were performed to investigate the stress conditions of D500 pipeline under operational conditions, assuming there were no pre-existing cracks. Such analyses are useful to obtain the nominal stresses of the pipelines. Analyses were also performed to investigate the effects of bell joint in the analysis. Figure 4-2 and Figure 4-3 show the induced stresses in the pipelines with and without the presence of the bell joint respectively. As it can be seen, D500 pipeline is subjected to a maximum stress of ~ 13MPa which occurred at and around the elbow junction. The failed UL pipe (in the direction of Ultimo Lane) was subjected to a maximum stress of ~11MPa. These stresses are well below the pipe failure stress of around 100 MPa (Ref. [10]). These results indicate that the presence of a joint has not significantly affected on maximum stress induced on D500 pipeline if no pre-existing cracks exist in the pipe.



(a) Both pipes (b) Enlarged cut of the elbow jointed pipe

**Figure 4-2 Pipe stresses (in KPa) during operation at no presence of pre-existing cracks; but insertion of a bell joint into the model**

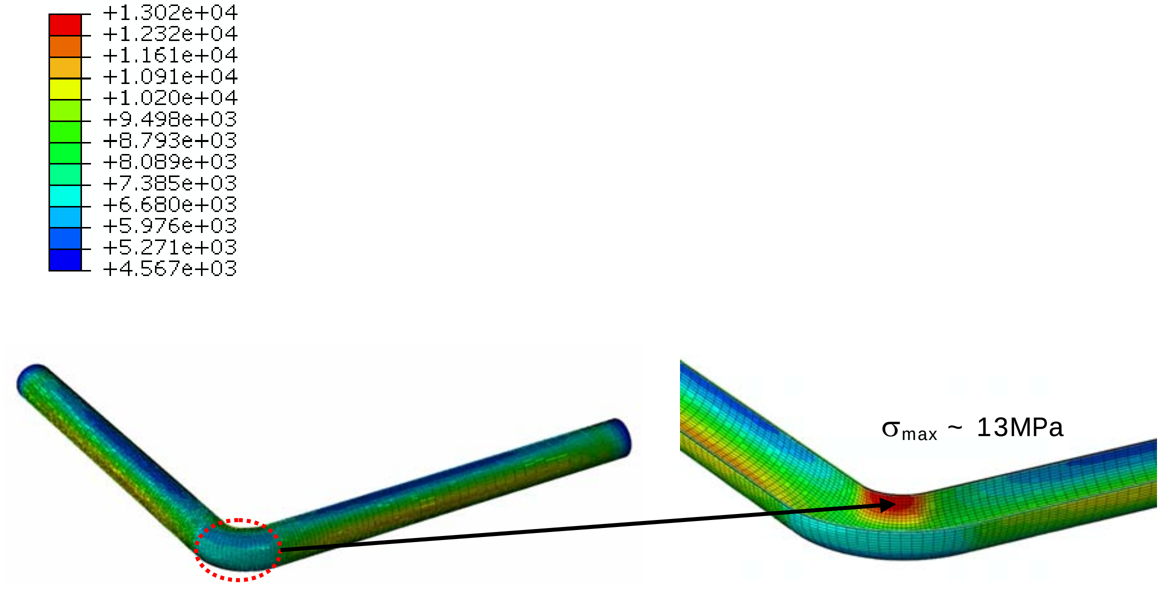


(a) Both pipes (b) Enlarged cut of the elbow pipe

**Figure 4-3 Pipe stresses (in KPa) during operation at no presence of cracks and joints**

### 4.3.2 Effect of D750 above the failed pipe

Analyses were also performed to see whether there were any effects from the over-laid D750 pipeline when operating at different water pressures (0.6MPa and 1MPa tested in the current study). Simulations were performed excluding the over-lying D750 pipe on the basis of the model without crack and bell joint. Results of the analyses are shown in Figure 4-4. As can be seen from the results, D500 pipe was induced a maximum stress of around ~13MPa similar to what was obtained at the presence of D750 pipe (see Figure 4-2). Further, maximum stress is only enhanced by 0.1MPa in D500 pipeline when the D750 pipeline is operated at higher pressures (i.e. 1MPa). This is because the deformations in D750 pipeline even at higher pressures are not substantial to increase soil loading beneath the pipe (i.e. above D500 pipeline).



(a) Elbow pipe

(b) Enlarged cut of the elbow pipe

**Figure 4-4 Pipe stresses (in KPa) during operation at no presence of over-laid D750 pipe as well as no pre-existing cracks**

### 4.3.3 Effect of the Anchor block at the elbow of D500 pipeline

It was noted (Ref. [7]) that there was an anchor block restraining the movements of the elbow junction as shown in Figure 2-1. Investigations were performed to see whether there were any effects from this anchor block on the stress state of D500 pipeline.

The effect of the anchor block was introduced into the FE model by specifying a local coordinate transformation to a set of nodes at the edge of the elbow in order to introduce horizontal restraints normal to the pipeline (see Figure 4-5).

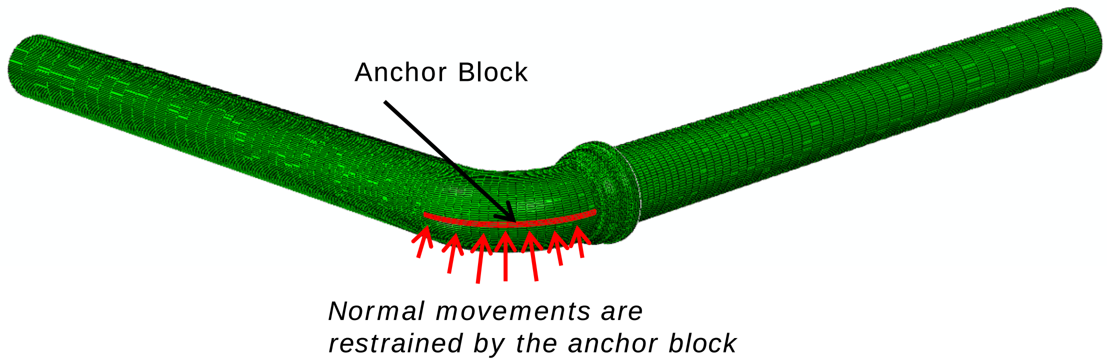
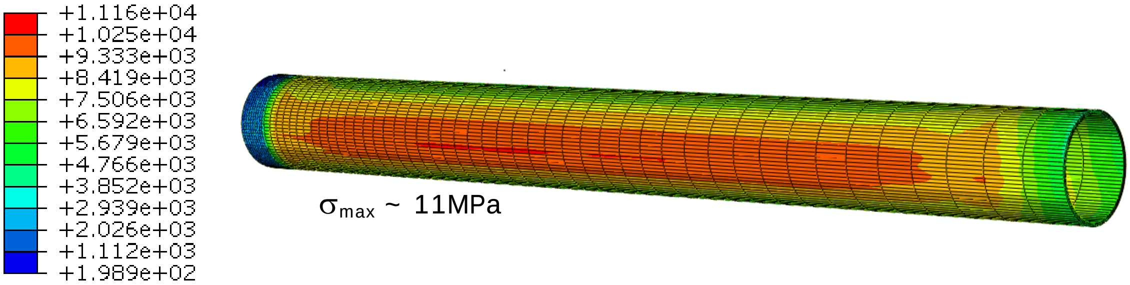
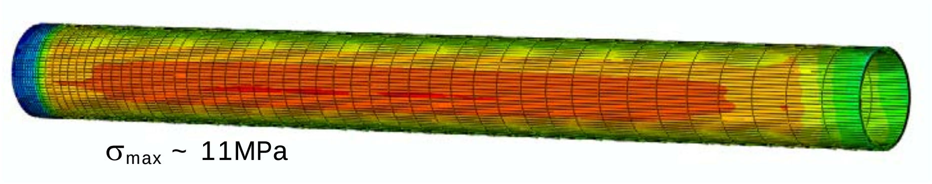


**Figure 4-5 Implementation of the influence of the anchor block into the model**

Figure 4-7 shows the results for the cases of with and without the anchor block respectively. It can be seen that the stress differences between these two models are negligible. This is because the movements at elbow section of the pipe are small even without the anchor block, for instance, the maximum amount of the lateral displacement of the elbow is only ~0.1mm when there is no anchor block to restrain the elbow displacements. However, the influence of soil's contribution to restrain the pipe was not investigated.



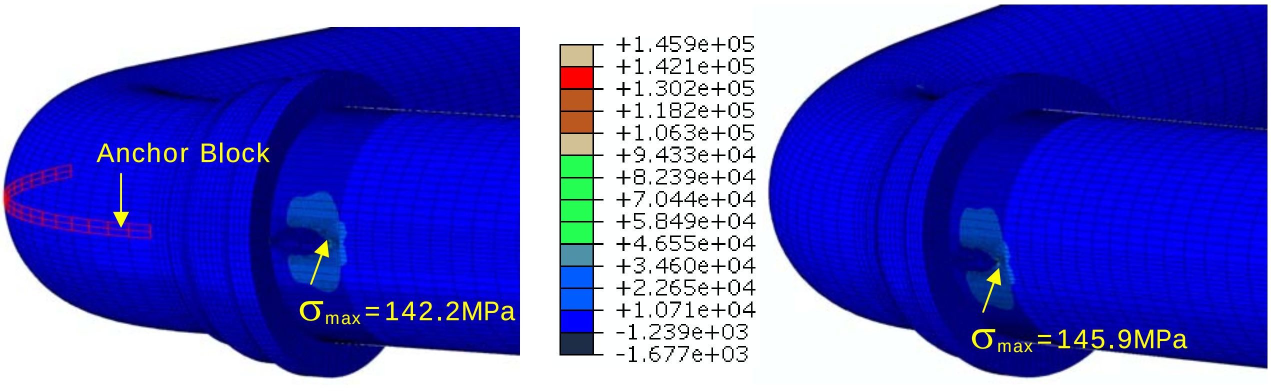
(a) Model with the anchor block



(b) Model without the anchor block

**Figure 4-6 Stress comparison of the D500 straight pipeline (No crack) between the cases of with and without anchor blocks**

The analyses results for the fracture models are shown in Figure 4-7 (a) and (b) for with and without anchor block models respectively. It shows that only ~3.5MPa difference in maximum stresses between the block and no block models. The influence of soil's contribution to restrain the pipe was not investigated.



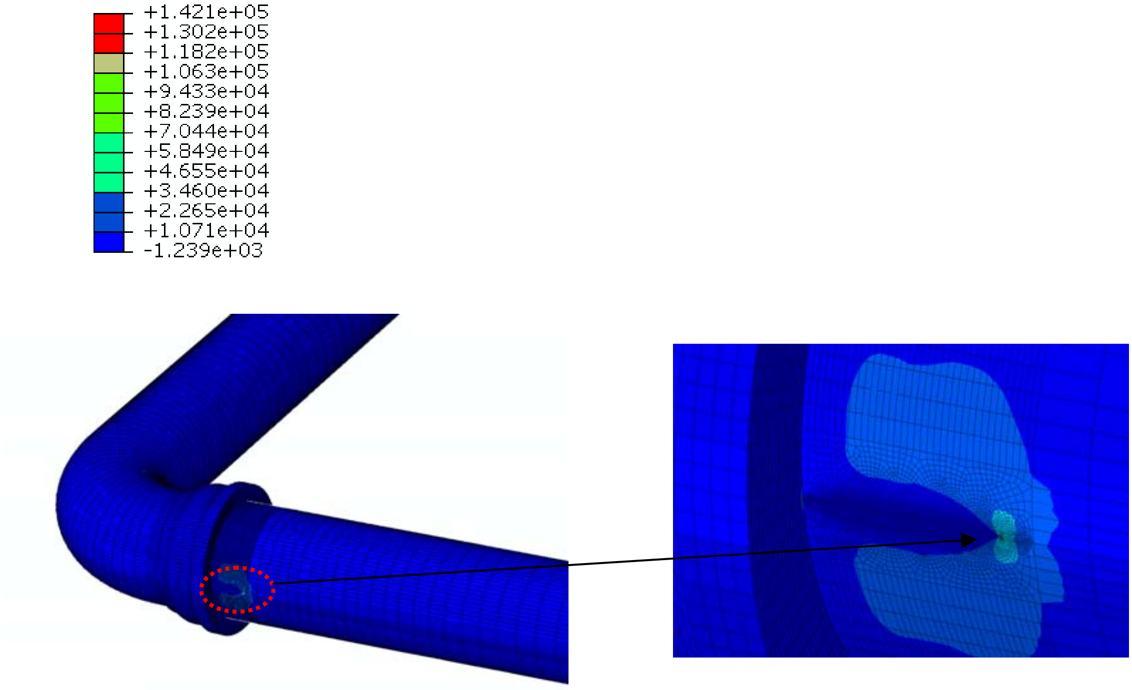
(a) Crack model with the anchor block (b) Crack model without the anchor block

**Figure 4-7 Stress comparison of the D500 straight pipeline (with crack; length 15cm) between the cases of with and without anchor blocks**

### 4.3.4 Effect of the presence of a pre-existing crack

It can be seen from the above analyses that the maximum stress in D500 pipeline would not exceed 13MPa during its normal operation provided that the pipe has no cracks or corrosion defects. However, the analyses undertaken by Metallurgist indicated that an older pre-existing crack was evident in the UL pipe (at a springline location) at the pipe bell end. Therefore, FE assessments were conducted to investigate the effects of a pre-existing crack located at the springline of the UL pipe (see Figure 4-8). Analyses were performed at different lengths of pre-existing cracks varying from 5cm, 15cm, 17.5cm, 22.5cm, 27.5cm, 32.5cm and 37.5cm. On the basis of bell dimensions assumed, the crack appears outside the bell section, once the crack length exceeds 17.5cm. Hence, the last five cases of crack lengths given above, represent unrestrained (outside the bell joint) crack lengths of 0cm, 5cm, 10cm, 15cm and 20cm respectively.

It can be seen from the results that the maximum stress of the D500 pipeline is always concentrated at the crack tip as shown in Figure 4-8.



(a) Elbow pipe with joint and crack (b) Enlarged view of the crack

**Figure 4-8 Pipe stresses (maximum principal) during operation at the presence of pre-existing crack in the bell joint (at a crack length of 15cm outside the bell joint)**

The results from all the analyses are summarised in Figure 4-9, in terms of maximum pipe stress observed at the crack tip versus the total crack length. The maximum stress increases at a smaller rate when the crack tip is inside the bell pipe. This is because the bell section can provide sufficient restraint to resist crack opening. Once the crack goes past the bell joint, the additional restraint is lost and hence pipe is subjected to larger stresses at the crack tip. Eq. 1 is calibrated to estimate the maximum stress ($\sigma_{\max}$) at a given crack length ($l_{cr}$).

$$\sigma_{\max} = -0.0003 l_{cr}^4 + 0.0191 l_{cr}^3 - 0.197 l_{cr}^2 - 0.1178 l_{cr} + 16.031$$ **Equation 1**

Where $l_{cr}$ is the *total crack length from the edge of the pipe.*

Once the crack propagates to about 10-15cm beyond the bell joint (i.e., unrestrained crack length), the maximum stress reaches the likely tensile strength capacity of cast iron (General tensile strength of uncorroded spun cast-cast iron pipes can be more than 70MPa, Ref. [11]). For instance, the SW test bed pipe section gave a tensile strength of 100 MPa (Ref. [10]). These results indicate that the pipe could undergo tensile fracture if the pre-existing crack propagated to 10 to 15cm outside the bell joint.

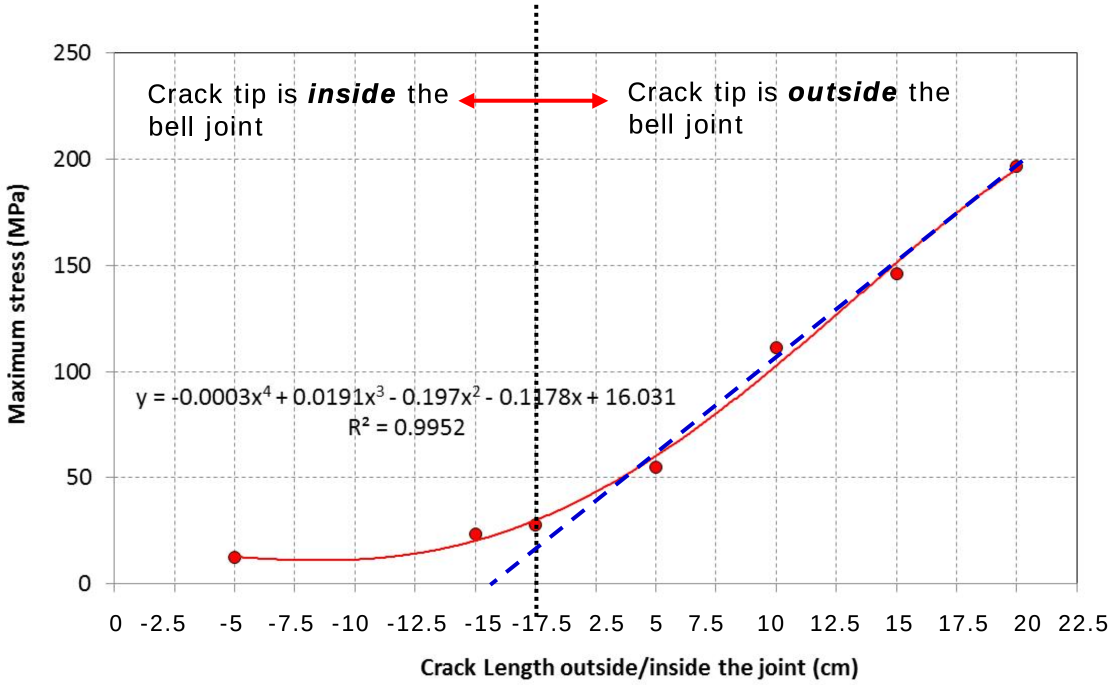


**Figure 4-9 Variation of maximum stress in D500 pipeline at different pre-existing crack lengths**

### 4.3.5 Failure assessments based on ‘Fitness-for-service’

Failure assessments were also conducted in accordance with FAD (Failure Assessment Diagram) – Level 2 assessments given in API 579 (Ref. [2]) and with the use of the results from FE analyses. The importance of FAD analysis is that it considers both stress concentration induced failure (i.e. tensile or yield strength) and stress intensity factor induced fast fracture (i.e. fracture toughness). Assessments were performed on the basis of the procedure given in Ref. [2] for a cylinder, having a through wall crack in the longitudinal direction. The membrane stresses are obtained from the FE results. According to the Ref. [2], the condition of the pipe can be detected from the FAD diagram having obtained the fracture ratio $\left(K_r = {K_I}/{K_{IC}}\right)$ and stress ratio $\left(L_r = {\sigma_{ref}}/{\sigma_{yield}}\right)$. The stress intensity factor $(K_I)$ and the reference stress $(\sigma_{ref})$ are computed on the basis of the procedure outlined in Ref. [2]. Fracture toughness $(K_{IC})$ and yield strength $(\sigma_{yield})$ of the pipe were assumed as $10MPa\sqrt{m}$ (Ref. [11]) and 40MPa (Ref. [10]).

The results of the assessments are shown in Figure 4-10 for D500 pipeline with different pre-existing crack lengths (5cm, 10cm, 15cm, 20cm, 25cm). It can be seen that the pipe fails once the pre-existing crack exceeds a length of 13.7cm. It should be noted that there are no provisions made in the Standard to cater for the effects from bell restraints. i.e. Results from the FE assessments showed only a mild increase in stress concentration (hence stress intensity too) when the crack tip is inside the bell joint. Once the crack is extended beyond the bell joint, stress started to increase rapidly. Such behavioural stress pattern does not capture in the current Standards.

According to the trend of the FE stress results beyond the bell joint (blue dashed line in Figure 4-9), the maximum stress at the crack tip would have reached ~100MPa (i.e. possible tensile failure) when the unrestrained crack length becomes 12.5cm. This value is in good agreement with the failure crack length (i.e. 13.7cm) derived from FAD level 2 assessments.

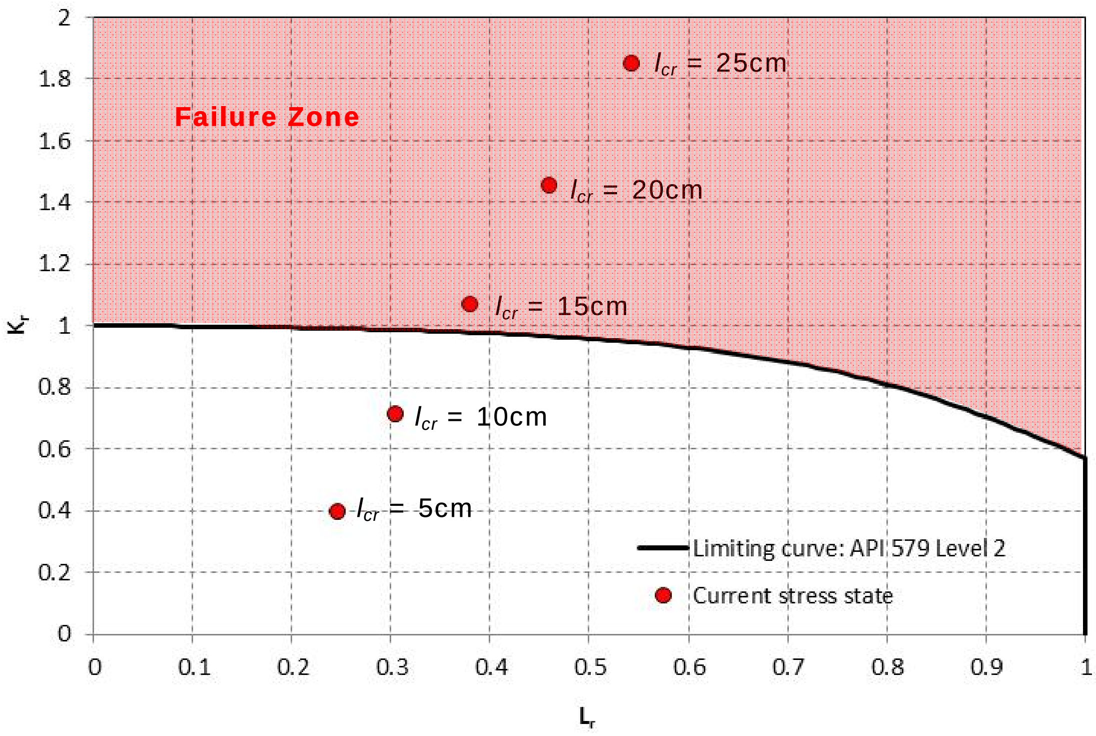


**Figure 4-10 API FAD-Level 2 Assessment**

### 4.3.6 A possible explanation for the cause of pipe failure

Analyses undertaken on uncracked pipe indicated that D500 pipeline is only subjected to a maximum stress of 13MPa. Under such condition, the failure is unlikely since the maximum stress is significantly lower than the tensile strength of cast iron which is typically in the range of >70 MPa (Ref. []11). However, Metallurgist's report indicated that there was a pre-existing crack in the Ultimo Lane section pipe at the bell location. The initiation of the crack might have caused either by corrosion or a manufacturing/construction defect or a combination of these possibilities. Such cracks initiated within the joint can be restrained by the bell joint, not producing high stress concentrations which can lead to catastrophic failures (maximum stress at the crack tip is small for $crack\ length < 0$ as shown in Figure 4-9). With further loading from static water pressure, water hammer and traffic loading, the crack may have grown in subcritical (below the failure stress due to fatigue; or damage accumulation due to repetitive loading from water pressure and possibly traffic loading) manner until it came out of the bell and into the unrestricted section of the pipe. When the unrestrained crack grew to a length of about ~10cm-15cm out of the bell joint (as supported by Metallurgist's report), the stress exceeds beyond 100MPa (see Figure 4-9), which was sufficient to cause the tensile failure. Such increase in stress also caused to increase the stress intensity factor and reference stresses large enough to reach the combination of $K_r$ and $L_r$ to the limiting failure surface as shown in Figure 4-10. This may have led to fast fracture and catastrophic failure of the pipe on the day 10th August 2013 at 11.05pm. As the crack extended along the pipe (on springline see Figure 2-1), the crack velocity could have increased and then the crack may have started to wonder and become wavy to dissipate extra energy, and finally may have blown a section out of the bell at the other side of the failed pipe.

## 5 SUMMARY AND CONCLUSION

A case study was undertaken on the pipe failure that took place at Harris Street and Ultimo Lane junction on the 10th August 2013 at 11.05pm. Due to the complexity of the case, several analyses were conducted to explain the possible failure mechanism of D500 pipeline. A summary of the findings is presented below.

- If the D500 pipeline was assumed to be crack free (there was no much corrosion found on the pipe), then, it is subjected to a maximum stress of around 13MPa which occurred at and around the elbow junction. The UL pipe was subjected to a maximum stress of ~11MPa. Analyses results also indicated that the presence of a joint has no significant effect on the maximum stress induced on the D500 pipeline provided that there were no pre-existing cracks in the pipe. ***Therefore, the pipe failure would not have taken place if the pipe did not have a pre-existing crack.***

- The results indicated that over-laid D750 pipeline appeared not to present major influence on the stresses developed in D500 pipeline. **This is because the deformations in D750 pipeline even at higher pressures are not substantial to increase soil loading beneath the pipe (i.e., above D500 pipeline).**

- **The study conducted to investigate the effects of the anchor block indicated that the stress differences arising from having an anchor block are negligible for both no-crack and for with-crack models (the maximum difference is only about 3.5MPa).** This is due to the fact that the movements at the elbow junction of the pipe are very small even without the anchor block support**. However, the influence of lack of soil support due to any erosion or softening was not considered.**

- Results on with-crack model showed that the maximum stress increases at a slower rate when the crack tip is inside the bell pipe. This is because the bell pipe is capable enough to provide an addition restraint to resist crack opening. Once the crack started to appear outside the bell joint, the additional restraint is lost and the pipe is subjected to larger stresses at the crack tip. **Once the unrestrained crack propagates to about 10-15cm, the maximum stress reaches the tensile strength capacity of cast iron and hence the catastrophic failure would have occurred on the day.**

- Failure assessments made on the basis of the fitness for service revealed that the pipe fails once the pre-existing crack exceeds a length of 13.7cm. It should be noted that there are no provisions made in the Standard to cater for the effects from bell restraints.

- The unrestrained crack length (i.e. no joint model) from FE, which incurs maximum stress of tensile capacity, has in good agreement with the failure crack length derived from FAD – Level 2 assessments.

- **The failure of the D500 pipeline can be explained through tensile fracturing as well as through fracture mechanics principles. The main driver for the failure in this case is the pre-existing crack, which may have propagated over the years through fatigue due to pipe pressure variations and to a lesser extent due to traffic loads.**

## 6 ACKNOWLEDGEMENT

This technical report is an outcome from the Advanced Condition Assessment and Pipe Failure Prediction Project funded by Sydney Water Corporation, Water Research Foundation of the USA, Melbourne Water, Water Corporation (WA), UK Water Industry Research Ltd, South Australia Water Corporation, South East Water, Hunter Water Corporation, City West Water, Monash University, University of Technology, Sydney and University of Newcastle. The research partners are Monash University (lead), University of Technology Sydney and University of Newcastle.

## 7 REFERENCES

1. ABAQUS, Inc. (2012), ABAQUS V.6.12 User's Manual, Providence, Rhode Island.

2. API 579, Recommended Practice for Fitness for Service; API 579. 2007, Ameriacan Society of Mechanical Engineers.

3. Austroads (2010). Pavement Design-A Guide to the Structural Design of Road Pavements, Austroad Inc.2010.

4. Heena shaikh, "Water coming out of the streets- Harris street and ultimo road. Sydney", Aug 10 2013, http://www.youtube.com/watch?v=VPXMyE0zOpM

5. Jaime Valls Miro (2013), [Jaime.VallsMiro@uts.edu.au], "RE: Harris st break" email message to Jayantha Kodikara, "RE: Harris St data", 9 December 2013 09:48.

6. J. Kodikara, D. Robert and J. Rajalingam, "Preliminary Analysis of Harris St/Ultimo Lane Pipe Failure", Report to Sydney Water, 8 Dec 2013.

7. Jeya Rajalingam (2013), [Jeya.Rajalingam@sydneywater.com.au], email message to Jayantha Kodikara, "Harris St data", 23/10/2013 10.18.

8. Jeya Rajalingam (2013), [Jeya.Rajalingam@sydneywater.com.au], email message to Jayantha Kodikara, "RE: Harris St data", 23/10/2013 11.26.

9. John, L Gray Pty Ltd (2013), Metallurgical investigation report, Report No: JLG04-668.

10. Robert, D.J., Kodikara, J., and Rathnayaka, S. (2014), "Failure modelling of cast iron supported by Laboratory test data", In preparation.

11. Seica, M.V. and Packer, J.A. (2004), “mechanical properties and strength of aged cast iron water pipes”, Journal of materials in civil engineering ASCE, Vol. 16, No.1, pp.69-77.

12. Valls Miro, J., Rajalingam, J. Vidal-Calleja, T., de Bruijin, F., Wood, R. Vitahage, D. Ulapane, N. Wijerathna, B. and Su D. (2013). A live test bed for the advancement and failure prediction research on critical pipes, Leading Edge Strategic Asset Management, LESAM 2013, 10-12 September, Sydney, Australia.