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Failure analysis of a high pressure natural gas pipe under split tee by computer simulations and metallurgical assessment

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ABSTRACT

Crack failure of a 36 inch high pressure gas pipe observed during regular inspection of a station has been investigated and the results are presented in this paper. The crack, approximately one meter long, was initiated from a notch inside the hot tapped hole in a pipeline installed about 30 years ago. The study was conducted by reviewing the design history and construction data, visual inspection, pipe material characterization, stress and modal analysis by using finite element method. Investigations revealed that the valve, directly connected to the split tee, faced large dynamic periodic forces due to a pressure drop between two pipelines. Metallurgical evaluation of the pipe material by optical microscope and fractography of the crack surface by scanning electron microscopy indicated the presence of elongated inclusions in the steel microstructure together with some indications of fatigue fracture as a poorly formed sawtooth profile. Based on dynamic analysis, it was found that the first mode shape, the maximum displacement and, therefore, the maximum stress were exactly situated within the crack initiation zone. It was concluded that the notch effect in the hot tapped hole, the position of the supports under the split tee and the presence of a large periodic stress were responsible for the initiation and fatigue propagation of the crack in the gas pipe.

1. Introduction

Pipelines carrying natural gas of high pressure need a high level of reliability, especially for those lines close to stations and residential areas. Critical inspection and analysis of the failed pipes help to find those positions with a high level of risk and, thus, prevent catastrophic failure of the pipelines. Cases involving failure of pipes carrying natural gas under split tee are scarce. Nevertheless, few leaks and ruptures, occurred in gas pipelines and petrochemical industries, can be found in literature. High pressure natural gas transmission pipeline (API 5L X60) in Pakistan [1] and a T-shape natural gas pipeline network (API 5L X52) near gas extraction plant in northern Mexico [2] are two recently published reports. In both cases, the material degradation caused by corrosion was identified as the main factor contributing to the failure of the pipes. Other examples of similar failures, but carrying liquid fuel, include a 52 km pipe (API 5L X52) in Kuwait [3] and another API 5L X46 pipe in Brazil [4]. Delayed cracking and transverse cracking have been reported as the causes of these pipes failures, respectively. Further investigation proved that the derived costs of these failures have been significantly high.

Recently, an increasing number of research works are using computer simulation as a tool to find out how the operational conditions of the materials are responsible for a failure and fracture phenomenon. For example, dynamic simulation has been

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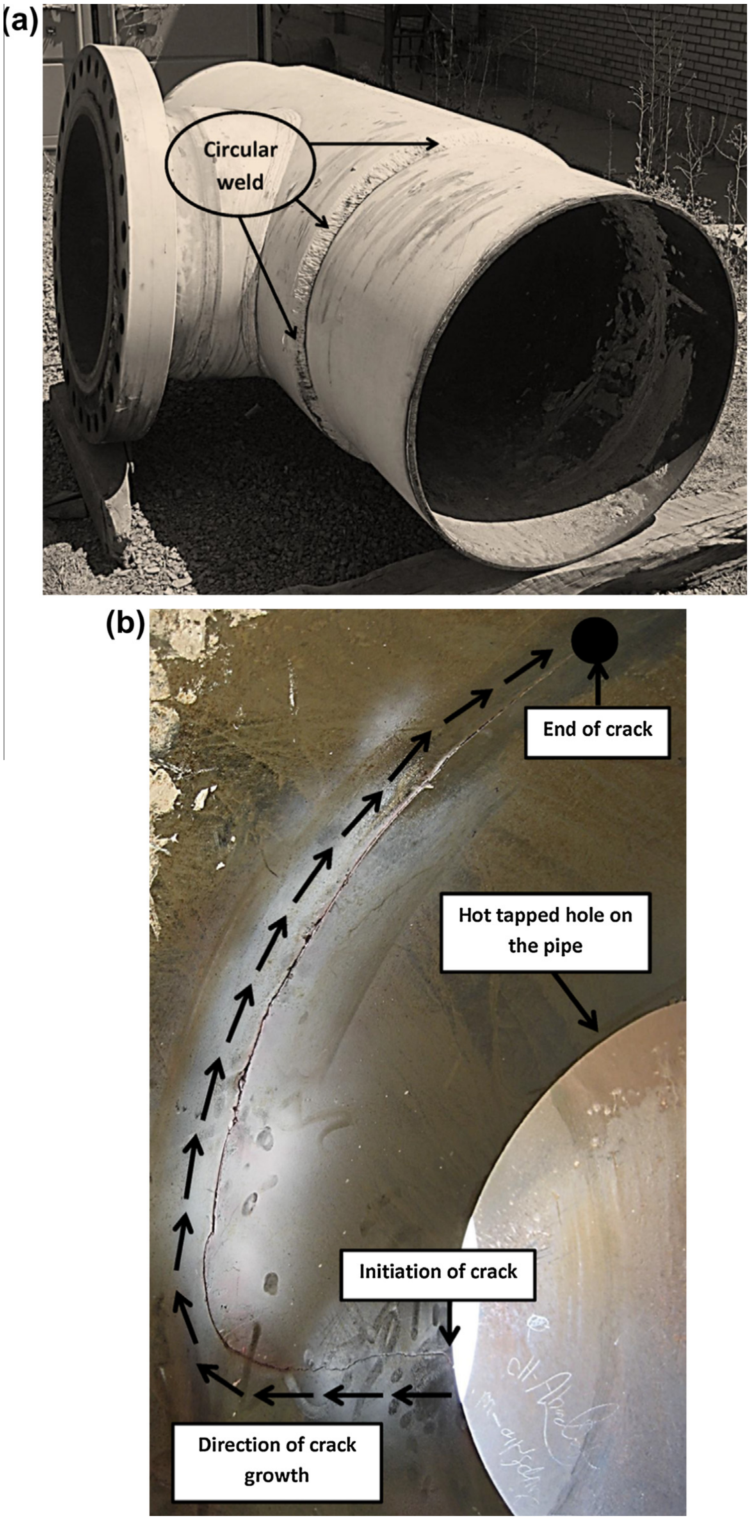


Fig. 1. (a) Front view of the damaged split tee and (b) crack inside the pipe under the split tee.

used to evaluate the stresses around flanges due to dynamic loads [5]. In another study, fluid dynamic simulations were performed to measure the depth of penetration of water into soil and its effect on corrosion of the gas pipeline [6].

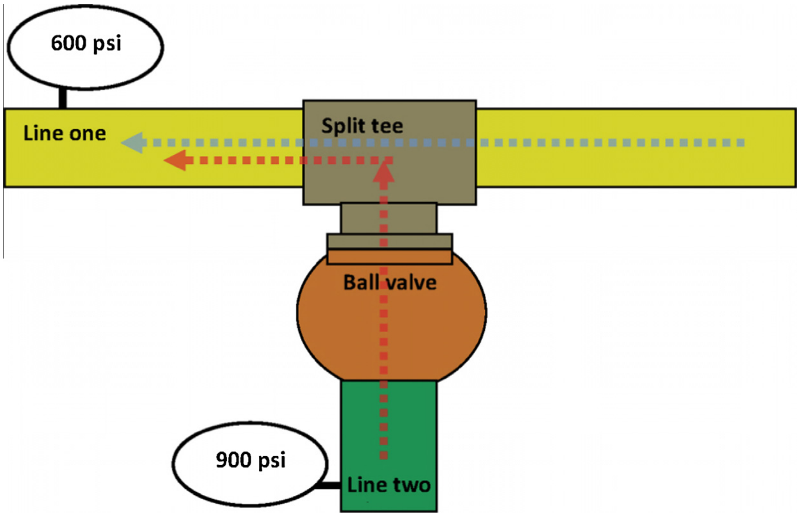


Fig. 2. Schematic of the split tee under work conditions.

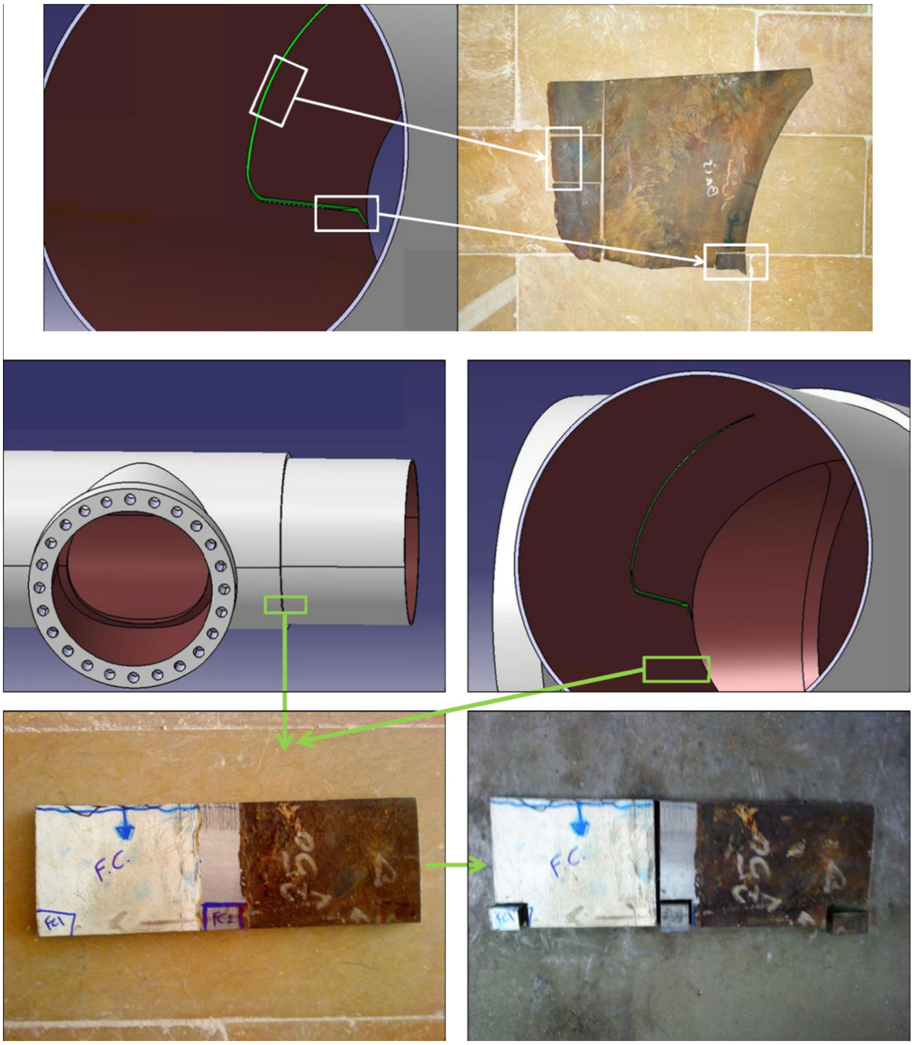


Fig. 3. Test samples prepared from the pipe material and their position on the failed pipe.

A case involving the failure of a high pressure natural gas pipe covered by a split tee, adjacent to a source of vibration, has been the subject of a comprehensive research by using metallurgical analysis and computer simulations. The failure was found during a periodic inspection check in a pumping station. A crack approximately one meter long was observed in a pipe under a split-tee connecting two major lines of high pressure natural gas. The results of this study are reported in the present paper with emphasis on the application of dynamic analysis to recognize the critical zone in the high pressure gas pipelines and the major mechanism responsible for the failure.

2. Methodology

The investigation conducted was comprised of four fundamental steps. First, review of the history information collected by visiting the station where the split tee was installed. Second was separating the split tee from the pipe by appropriate machining of the welded sections followed by preparation of specimens for testing and analysis. The third step included metallurgical examination of the cracks and pipe material followed by fractography of the sections. Finally, computer simulation was performed to find the critical zones and the areas of maximum stresses.

Fig. 1 demonstrates the damaged pipe and split tee after removing from the site and the crack inside the pipe. The crack has initiated from a point on the hot tapped hole and has grown in longitudinal direction, until arrested by the circular welds. In fact, by approaching the position of the weld, the crack changed its direction upward in a circular path.

Fig. 2 shows a schematic of the split tee under working conditions. Line 1 is the principal gas pipeline while line 2 is only used in occasions to compensate the pressure drop in order to maintain the pressure of line one at a desired level. The amount of gas flow from line 2 to line 1 was controlled through a ball valve connected directly to the spilt tee. On average, the pressure is approximately 600 psi in line 1 and 900 psi in line 2. The valve was operated manually to ensure a pressure of 600 psi in line one. Due to the pressure drop of 900–600 psi and the energy loss by this ball valve, the valve was rigorously vibrating with a frequency range below 100 Hz. The connection between the two lines has been produced by hot tapping process, thereby, the ball valve was connected directly to the split tee.

Split tee is a major part of the assembling process to make a T-junction on high pressure pipelines by hot tap operation. Hot tapping, or pressure tapping, is the method of making a connection to an existing piping by using a hole saw to make an opening in the pipe, so a line plugging head can be inserted. In this process, first the split tee is attached to the pipe with circular weld joints, then, the saw tool cuts an oval shape in the pipe. More details on hot tapping process have been described by Nippard [7].

To separate the failed pipe from split tee, the longitudinal and circular welds were removed by machining operation at room temperature to ensure that metallurgical specifications of the pipe material were not affected. Machining process was also employed to prepare the required specimens by cutting the pipe into smaller pieces. During cutting operation, it

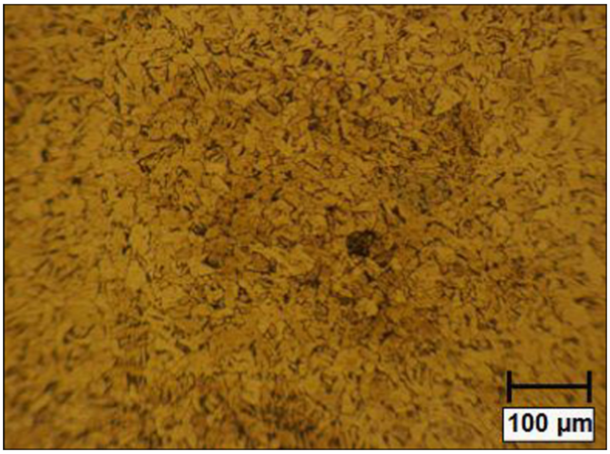


Fig. 4. Typical optical micrograph of the cracked pipe material.

Table 1
Chemical compositions of the pipe material and X60 steel (wt.%).

Specimen	C	Si	P	S	Mn	Ni	Cr	Mo	Cu	Al	V	Fe
Cracked pipe	0.188	0.51	0.035	0.02	1.59	<0.03	<0.01	0.04	0.04	0.08	<0.003	Rem.
X60 steel	0.21	0.45	0.025	0.02	1.60	0.3	0.3	0.10	0.25	0.06	0.15	Rem.

was noticed that the crack was growing through the thickness such that the pipe body was separated into two parts. Fig. 3 shows a schematic of the prepared samples and their position on the cracked pipe.

3. Metallurgical evaluation

3.1. Microstructural examinations

Standard metallography techniques were employed to study the microstructure of the test pieces. Fig. 4 shows a typical optical micrograph of the pipe material; the structure shows a fine, equiaxed two phase steel consisting of a ferritic matrix with embedded pearlite as dark regions.

Voids and microcracks can nucleate at the ferrite–pearlite interface close to the localized plastic deformation zone, especially for elongated ferrite and pearlite grains. In fact, the elongated ferrite and pearlite can help in nucleation of narrow, stretched void and microcracks. However, the equiaxed pearlite grains also consist of lamellar cementite in a ferrite matrix. It is well known that, this type of microstructure can be subject to a new source of void and microcrack nucleation during plastic deformation under compressive loading [8]. However, neither void nor microcrack was observed in the optical micrographs of the pearlite grains. Thus, it can be stated that the failure in the present work, is not directly attributed to the microstructure of the pipe material.

The composition of the steel pipe was determined by optical spectroscopy and compared with nominal composition of X60 steel (Table 1). It can be seen that the pipe composition is in good agreement with the standard X60 steel, although the pipe was 30 years old built at a time when this material was not that common.

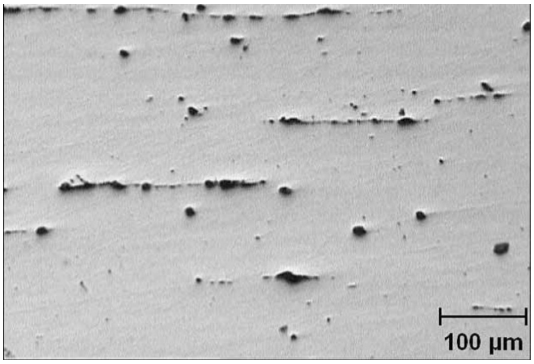


Fig. 5. Distribution of inclusions in the cracked pipe material.

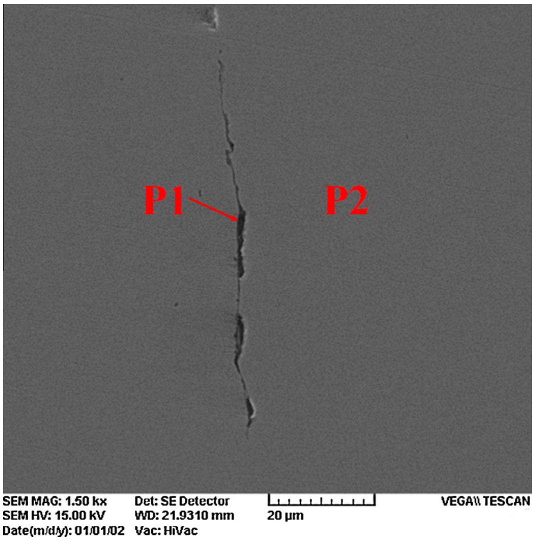
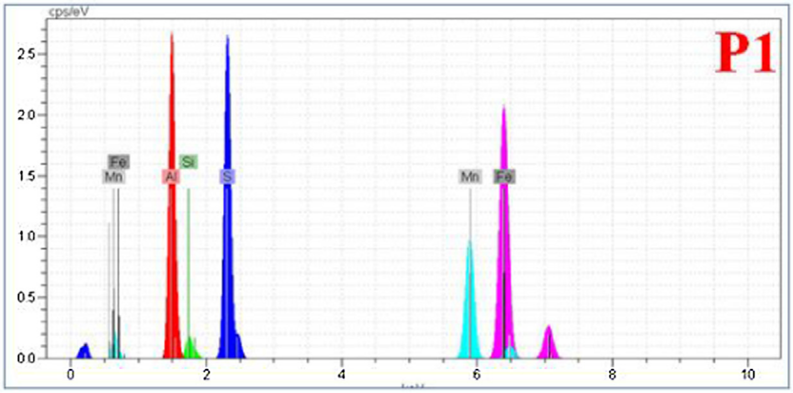


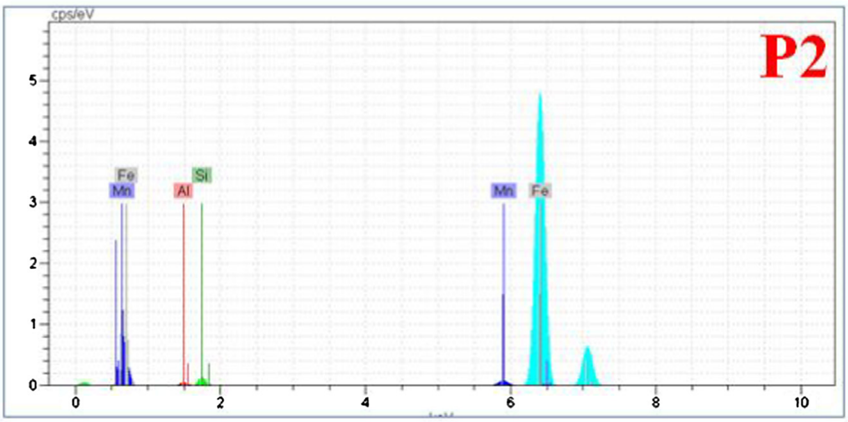
Fig. 6. Positions of spots for microanalysis by EDS; point P1 is located at the inclusion and point P2 is on steel matrix.

(a)



Element	Series	Unn. C	Norm. C	Atom. C
		[Wt. %]	[Wt. %]	[At. %]
Al	K series	15.77	16.42	26.55
Si	K series	1.14	1.19	1.84
S	K series	11.64	12.13	
Mn	K series	17.77	18.51	14.69
Fe	K series	49.69	51.75	40.42
	Total:	96.0 %		

(b)



Element	Series	Unn. C	Norm. C	Atom. C
		[Wt. %]	[Wt. %]	[At. %]
Al	K series	0.28	0.26	0.53
Si	K series	0.58	0.53	1.05
Mn	K series	1.27	1.17	1.18
Fe	K series	106.51	98.04	97.24
	Total:	108.6%		

Fig. 7. Results of EDS analysis performed; (a) typical elongated inclusion (P1) and (b) steel matrix around the inclusion (P2).

Several specimens were cut in longitudinal direction of the pipe wall, near the crack and far from that Fig. 5 illustrates an optical micrograph of the as-polished sample showing many dark regions within the microstructure; identification of these regions by EDS analysis was carried out and it was found that they were composed of sulfide and alumina inclusions (Figs. 6 and 7). Inclusions, second phase particles and grain boundaries are known as the susceptible sites for void nucleation and initiation of ductile failure. Many researchers have found that inclusions serve as void nucleation sites under compressive loads [8–13]. For this reason, the inclusion content should not exceed the specified limit for the material. In addition, the

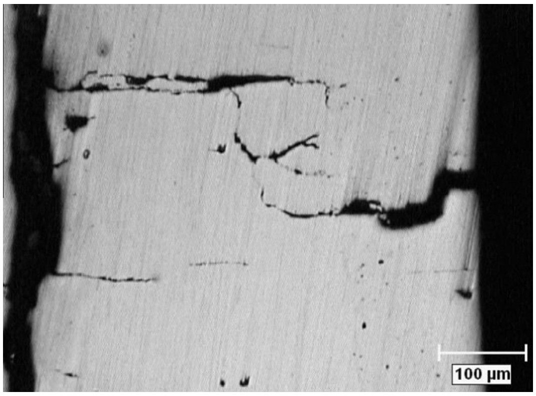


Fig. 8. Typical microcracks originated from the major crack along the inclusions.

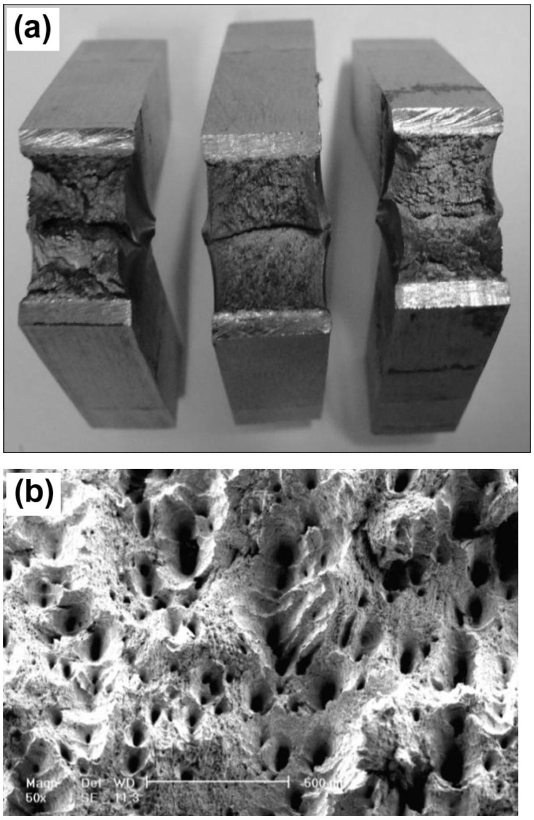


Fig. 9. (a) Impact test samples and (b) a typical fracture surface.

inclusion size is very important because large inclusions are the most harmful to the mechanical properties of the components. It is evident in Fig. 5 that a large number of inclusions were embedded in the pipe material as parallel arrays, thin but rather long. Although the inclusions were expected as spherical particles in API steel, some elongated shapes appear as parallel rows in the rolling direction. Chemical analysis of points P1 (located on a long inclusion inside the crack) and P2 (within the steel matrix) revealed high percentages of aluminum, manganese and sulfur, confirming alumina and MnS inclusions. As a general rule, such elongated inclusions are considered to be detrimental to the toughness of the material.

Fig. 8 shows several microcracks in the longitudinal direction of the pipe wall, connected to the major crack through the thickness. Careful examination of a sample, prepared at the vicinity of the major crack, indicated some microcracks originated from that along the inclusions that serve as a means of crack path. Elongated type inclusions might act as preferential sites for propagation of pre-existing cracks [10–12]. An inclusion can easily serve as a stress concentration site because of the

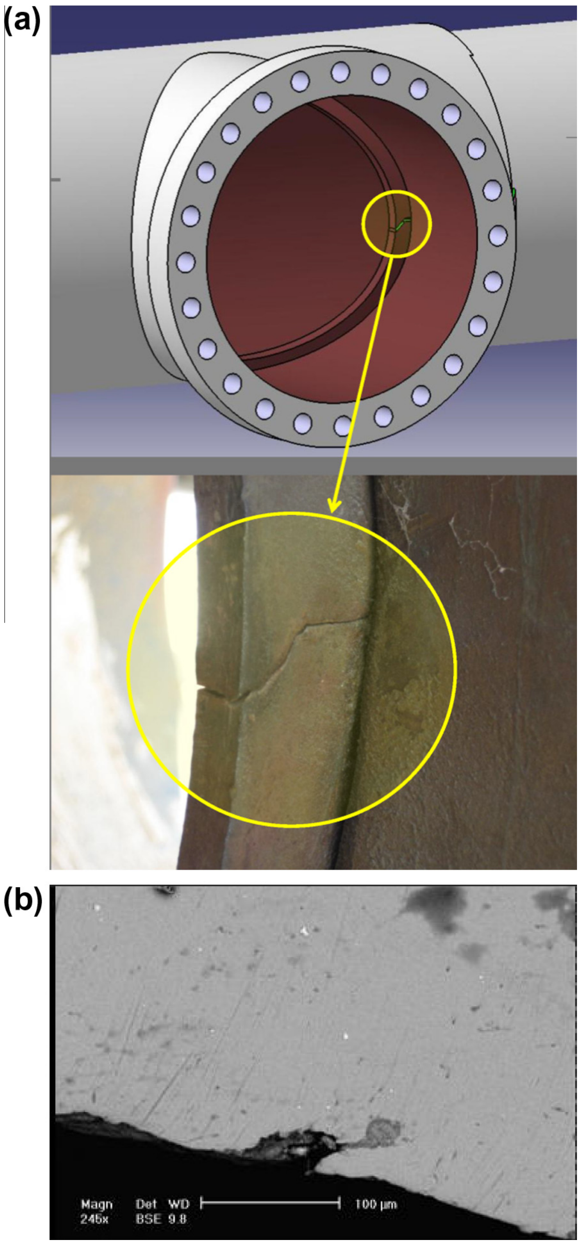


Fig. 10. A dent found inside the hot tapped hole where the crack was initiated; (a) approximate position of the dent on the oval hole and (b) SEM micrograph of a typical dent.

discontinuous nature and the lack of compatibility with the matrix material. Further examination of Figs. 5 and 8 demonstrate that inclusions are non-uniformly distributed within the steel microstructure, enhancing the formation of voids and a path for easy growth of microcracks. Nevertheless, there was not sufficient evidence to confirm that inclusions were the major cause of pipe failure.

3.2. Fractography

Fractography was carried out using scanning electron microscopy on both the crack faces and the fracture surface of the samples after impact testing. Typical fractographs of impact samples, presented in Fig. 9a, indicates that fracture has a ductile morphology. At low temperatures, ductile fracture usually involves the nucleation, growth and coalescence of voids in a plastically deforming material. Void nucleation normally occurs in the presence of inclusions and is caused by debonding of the inclusion from the surrounding material [10]. In fact, due to the flow of matrix material around the inclusions, the big spherical inclusions rotate. This leads to debonding at the interface between the inclusion and the matrix material. Thus, the

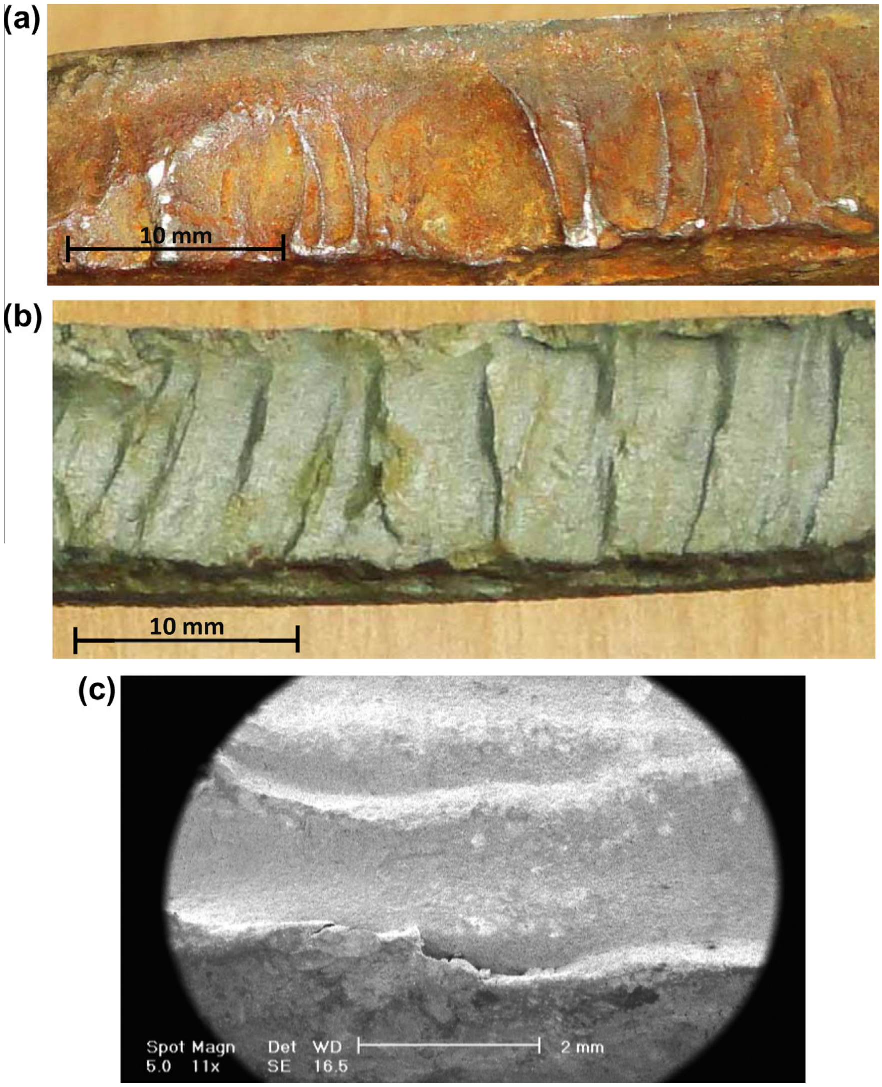


Fig. 11. Macrographs showing a typical zone of the crack face; (a) fracture surface covered with corrosion products, (b) fracture surface after cleaning in acid solution and (c) SEM micrograph of two adjacent ridges on the fracture surface.

Table 2
Results of hardness tests at selected points.

Position	Hardness (HV)
Base metal	190 ± 4
HAZ	186 ± 5

inclusions act as stress risers and can support void nucleation, growth, and coalescence, leading to ductile fracture mechanism. The oval shape of some of the voids in Fig. 9b is consistent with the elongated inclusions observed in the optical micrographs of the pipe material.

The surface of the hot tapped hole was examined for any indication of surface irregularities that might exert notch effect, producing stress concentration. Although, after many years from the failure time, the pressure in the pipe caused erosion of sharp edges and corrosion products covered all exposed surfaces, a type of damage was identified as a dent inside the hot tapped hole as shown in Fig. 10. Mechanical damage could have been occurred from the equipment during hot tapping process. Heavy oxide deposits on the crack surface proved severe corrosion of the fractured faces during a long time exposure after cracking. Further examination of the failed pipe confirmed that the main crack has initiated from the dent with its notch effect and progressed along the pipe during operation.

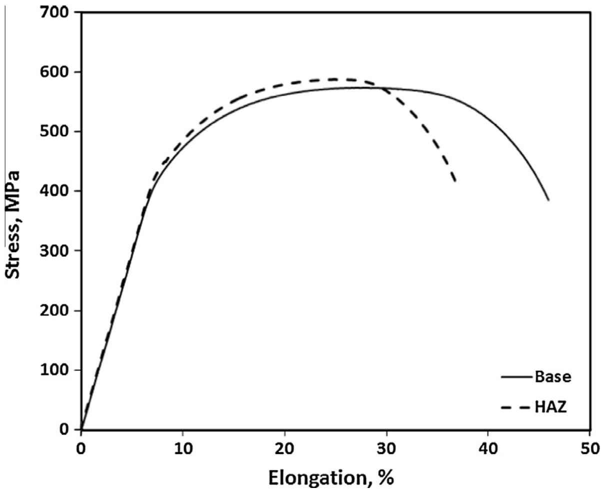


Fig. 12. Engineering stress–strain curves for the pipe material at two positions; base metal and heat affected zone.

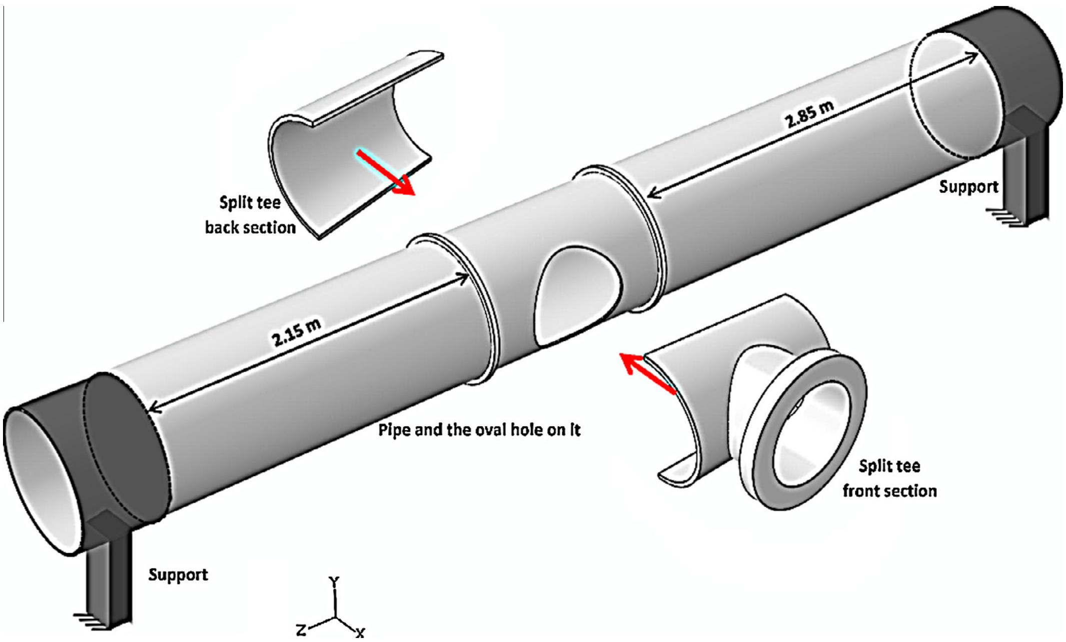


Fig. 13. Four major elements of the analysis; pipe, back section and front section of split tee and position of the supports.

Fig. 11 shows a typical zone of the crack faces prepared from the pipe wall thickness before and after acid cleaning. The fracture surface in Fig. 11a, covered with a layer of corrosion products, is composed of irregular ridges. After thorough cleaning of the surface in acid solution, the structure of the crack surface indicated rather uniform ridges spaced 2–4 mm apart from one another, Fig. 11b. Such a poorly formed sawtooth profile can be attributed to a fatigue fracture; the fracture surface could have been resulted from combined stage I and stage II fatigue crack propagation [14]. Further examination of the crack faces revealed a steplike appearance indicative of discontinuous growth; these are expected to occur under conditions of high through-thickness strains in structural steels. The steps appear as macroscopic beach marks, or clamshell markings, either radiate away from the crack origin or lie as parallel ridges. These are a special form of progression mark commonly associated with low cycle fatigue. When the propagation zone was examined by SEM, no beach mark was resolved on the fracture surface that was prepared by acid cleaning, instead, a featureless region was observed between the adjacent ridges, Fig. 11c. Nevertheless, based on the macroscopic observations of the fracture surface, it may be concluded that a fatigue mechanism has been involved in the process of crack growth during service life of the pipe.

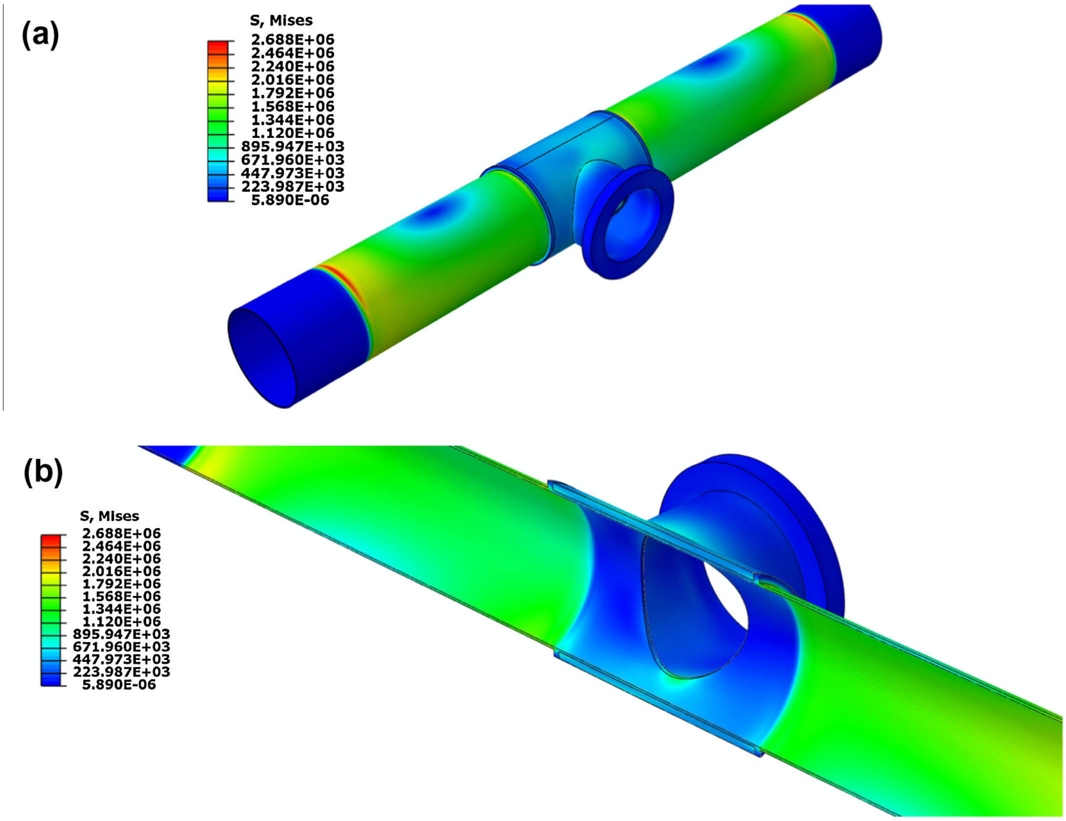


Fig. 14. Stress distribution due to gravity (a) front view and (b) cut of the back view.

3.3. Mechanical properties

Since the heat affected zone (HAZ) is a potential source of crack propagation, the mechanical properties of pipe material were evaluated at the HAZ and areas far from the weld zone. Hardness tests were carried out at many points on various positions of the pipe; the results are presented in Table 2 and show good consistency.

Typical stress–strain curves obtained from the tensile tests are shown in Fig. 12. The graphs were essentially similar in strength level, but the sample machined from HAZ had lower elongation compared to that of the base metal. Nevertheless, both the HAZ and base metal elongations were within the standard range for X60 steel.

Based on the results obtained from metallography and mechanical testing, no significant difference was recognized between HAZ and the base metal and, therefore, it was concluded that welding operation and properties of HAZ could not be responsible for cracking of the pipe in the present investigation.

4. Computer simulations and mechanical calculations

To find the critical areas with maximum stress and assess the stress in the regions susceptible to crack growth, mechanical and computer simulations were employed in two steps by using finite element method; stress analysis and modal analysis. The stress analysis was carried out to evaluate the effect of gas pressure and the pipe weight on the stresses generated on the pipe wall, while modal analysis was performed to calculate the natural frequencies and mode shapes of the pipe and split tee with respect to the position of the supports.

4.1. Stress analysis

The finite element static analysis was employed as a reliable technique for stress calculations. For a better clarification of the position of the supports and other parts of the failure system, Fig. 13 shows a schematic of four main elements; pipe, front section and back section of the installed split tee and the position of the supports.

The split tee is rather a heavy part. In order to consider the effect of the weight of pipe and split tee on stress distribution, the gravity was set as the external force and the stresses were taken into consideration. Fig 14 shows the results where the unit indicated for stress contour is Pascal. The results indicate that the stress exerted from the weight of split tee and pipe are

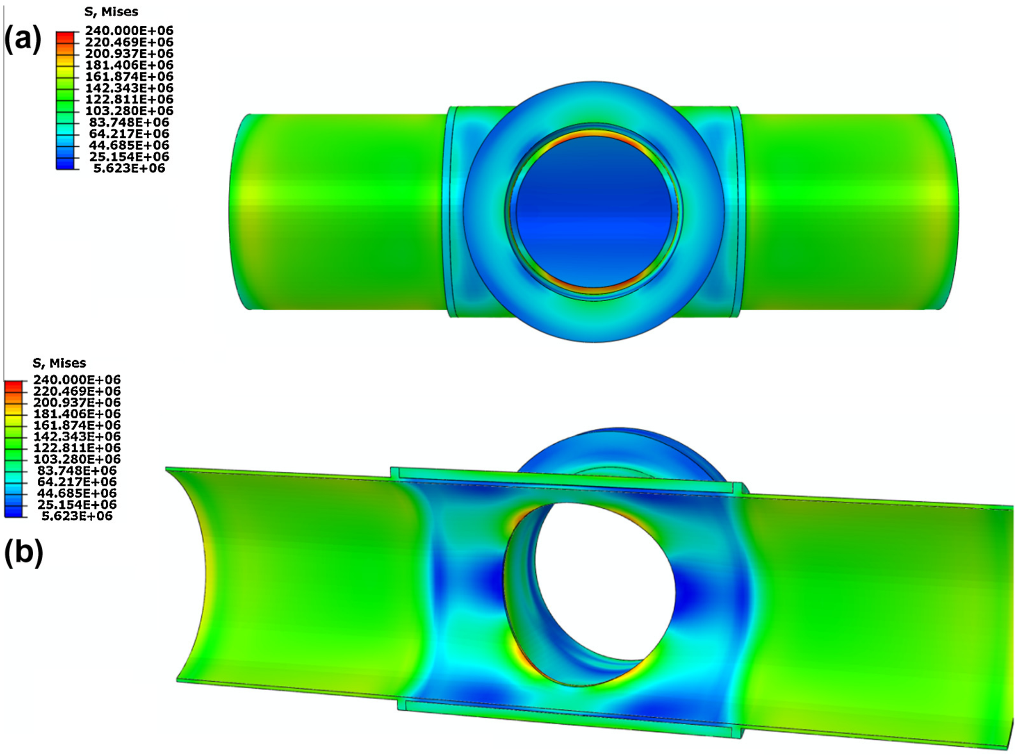


Fig. 15. Stress distribution due to the gas pressure; (a) front view and (b) cut of the back view.

Table 3
The first five natural frequencies of the pipe and split tee set.

Number	Frequency (Hz)
1	68.9
2	71.3
3	107.8
4	120.6
5	127.6

low and may be neglected in comparison with the stresses developed due to the inner gas pressure. The maximum bending momentum occurs at positions of the longest length and this happens near the supports. Accordingly, the highest values of Von-Mises stresses are positioned in this area. Considering Fig. 14b, one may note that the stresses due to parts weight, on the area that the crack was propagated are very low and, consequently, the weight of pipe and split tee cannot be responsible for this failure.

Fig. 15 demonstrates the results of stress distribution caused by the gas pressure inside the pipe; the highest value of stress is 240 MPa which is well below the yield strength of pipe material. In addition, the areas of high stress are not positioned on the regions that the crack has grown. Therefore, if the gas pressure was responsible for crack propagation, the crack should have initiated and progressed somewhere closer to the regions of high stress values.

The static analysis demonstrated two important facts:

(1) The stresses due to the weight of pipe and split tee, in comparison with the stress from gas pressure, are negligible.
(2) Although the gas pressure leads to areas of high stress in the vicinity of the oval hole, it could not be responsible for a crack initiation by itself.

4.2. Modal analysis

As mentioned earlier, the pipe was facing rather intense vibration and dynamic loads due to the valve vibration since it had direct connection to the split tee. This means that static analysis was not adequate; evaluation of dynamic characteristic of the system was necessary as an approach to this failure. To this end, dynamic simulations and modal analysis were

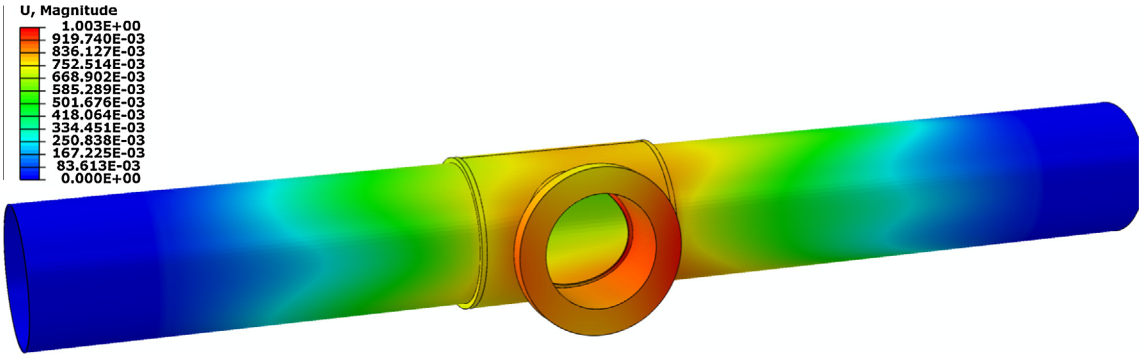


Fig. 16. The first mode shape of the pipe and split tee set.

Table 4
The first five natural frequencies for the new position of supports.

Number	Frequency (Hz)
1	204.8
2	218.6
3	252.9
4	256.9
5	305.1

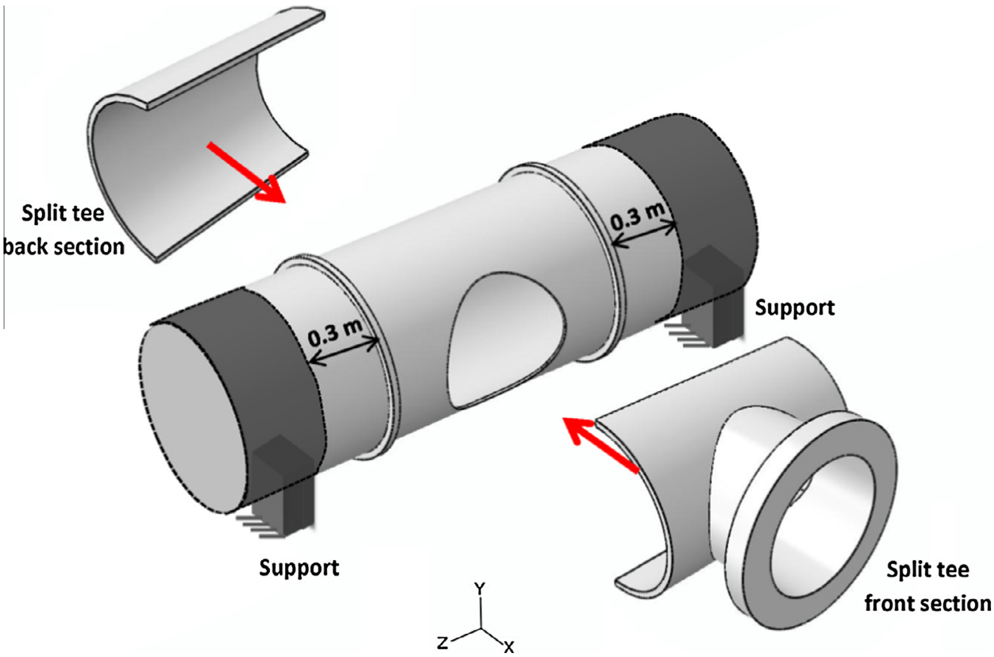


Fig. 17. The new position for the supports (0.3 m far from split tee).

performed, by using finite element method, in order to calculate the natural frequencies of the pipe and split tee under actual conditions, i.e., real position of the supports in the gas station.

Table 3 shows the first five natural frequencies of the whole system and Fig. 16 presents the first mode shape of the pipe and split tee. It can be seen that the maximum displacement is located exactly where the crack was initiated. Obviously, the maximum displacement would lead to maximum stress in this zone. The first natural frequency of the system is 69 Hz that is a rather low frequency, especially for a gas pipeline system under vibration. But, it must be noticed that in gas pipeline systems connected to the valves or other sources of vibration, the excitation frequency is generally below 100 Hz [9]. Hence, modal analysis proved that the system has not been sufficiently stiff with a low natural frequency for gas pipeline. Moreover, the maximum displacement and, consequently, the peak stress were situated in the area where the crack was initiated.

It can be concluded that if the position of the supports had a shorter distance to the split tee (e.g., 0.3 m compared to previous value as shown in Fig. 13), the first natural frequency would have been more than twice the previous situation (Fig. 17). Under such condition, the natural frequencies (Table 4) would have been in excess of 100 Hz and, consequently, less energy would be absorbed by the system, the level of dynamic stresses would be decreased; the initiation and propagation of crack along the pipe could be inhibited.

5. Conclusions

The factors leading to the failure of high pressure gas pipe covered by split tee were investigated in this paper. The primitive study proved no sign of stress corrosion cracking or related issues responsible for this failure. On the other hand, dynamic analysis confirmed that the system had comparatively low natural frequencies for a gas pipeline system. Since a huge energy level was involved, the ball valve was severely vibrated with a frequency range below 100 Hz. This means the valve was the vibration source in this system and, as the natural frequency of the system was near the motivation frequency, a lot of the vibration energy was being absorbed by the set of pipe and split tee, leading to an increase in the amplitude of the vibration and, thus, development of dynamic stresses. As in the first mode, the maximum displacement was positioned in the area that the crack was initiated. Hence, due to dynamic stresses, the crack has begun from a notch present on the hot tapped hole. Then, dynamic loads and the pipe inner pressure caused the crack to propagate in the longitudinal direction of the pipe by a fatigue mechanism; a vibration-induced in-service cracking. When approaching the weld zone, the crack was arrested where it faced a thickness almost 3 times bigger than the thickness of the pipe wall. The crack then changed its direction toward circumference and, finally, stopped growing when approached the low stress zone. Appropriate design of distance between supports is suggested as a remedy to the problem.

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