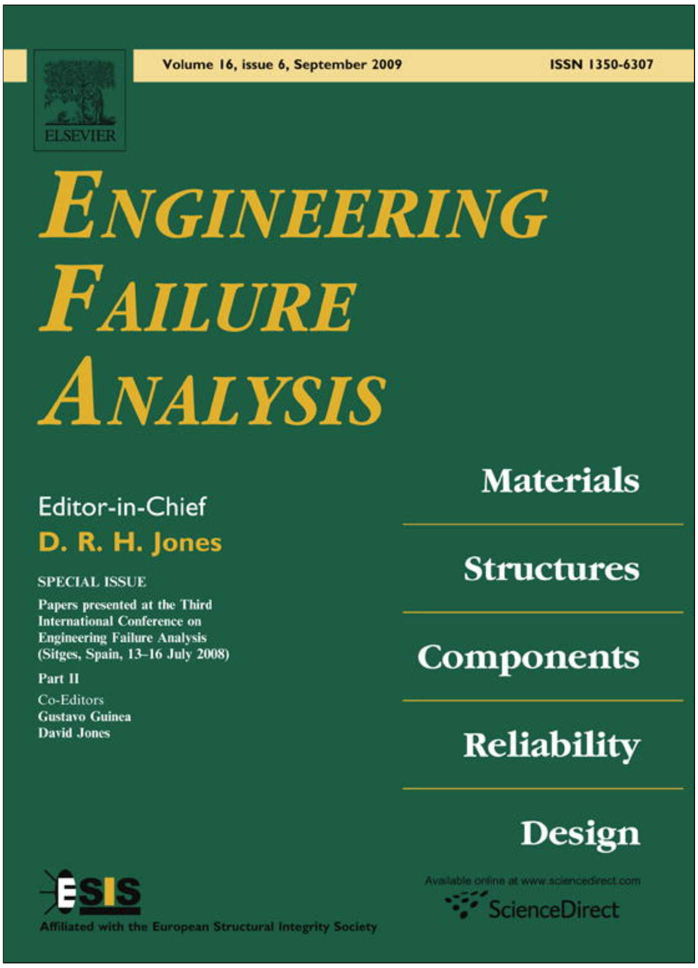
Volume 16, issue 6, September 2009
ISSN 1350-6307
ELSEVIER
ENGINEERING
FAILURE
ANALYSIS
Editor-in-Chief
D. R. H. Jones
SPECIAL ISSUE
Papers presented at the Third International Conference on Engineering Failure Analysis (Sitges, Spain, 13–16 July 2008)
Part II
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Materials
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Components
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ESIS
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Available online at www.sciencedirect.com
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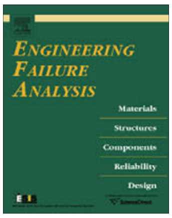
Engineering Failure Analysis 16 (2009) 1912–1921

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



Failure analysis of flexible metal hose at compressor discharge

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ARTICLE INFO

Article history:
Received 16 September 2008
Accepted 23 September 2008
Available online 8 October 2008

Keywords:
Fatigue crack growth
Compressor
Wear
Hosepipe
Vibration

ABSTRACT

Flexible hoses are sometimes placed at compressor discharge to minimize the effect of vibrations on piping and vessels. Doing well for this purpose, these elements can suffer dynamic loads from gas pulsation and fail. The root cause of the failure of a flexible connection at the discharge of an oil distillery propane alternating compressor is investigated. The connection is a 150 mm stainless steel corrugated metal hose with an external braid. The failure took place by overload of the braid, after wear of the wires. The fractures in the wires were consequence of fatigue crack propagation in previously worn areas. It was found that the flexible connection was under a larger working pressure than the maximum allowable as defined by the manufacturer. The failed flexible had thinner wires and different braid design than those previously used by the user. Recommendations include procedures to verify dimensions previous to assembly and to increase the inspection frequency of these elements, as well as to verify vibration levels of the connected machines. An elastomer material placed between corrugated and braid would diminish the rate of wear caused by vibrations.

1. Introduction

The purpose of the present analysis is to determine the origin of the failure of a flexible connection at the discharge of a propane alternating compressor at a petrochemical plant, in order to define the strategies for evaluating and insuring fitness for service, integrity and life extension. The flexible connection is a 150 mm diameter corrugated metal hose with an external braid, both of stainless steel. The flexible system was installed many years ago, in replacement of rigid piping that produced fatigue problems in the compressor discharge vessels. These failures are not recurrent, but the associated risk determines the relevance of the study to determine the root causes and eventually develop alternative designs or mitigation proceedings. The work done was conducive to establish constructive, operative and materials conditions that lead to the reduction of the useful life of the component.

The failed flexible hose is made of AISI 304, has an inner 0.6 mm thick, longitudinally welded, annular corrugated hose of diameter 6 in., covered by a single braid of same material (Fig. 1). The wire of the braid is 0.6 mm diameter. Both ends have sleeves and flange fittings. The failed flexible, identified as "short elbow", was at the discharge of the propane compressor, working under a maximal pressure of 13 bar (Fig. 2). Two different kinds of braids can be identified in the installed flexible hoses, the difference does not obey to the unlike operational conditions where they are working, discharge an intermediate pressure, but to modifications in braid design introduced by the manufacturer. Both kinds of braids are supposed to be

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doi:10.1016/j.engfailanal.2008.09.031

Fig. 1. Failed flexible hose at the discharge of a propane compressor.

Fig. 2. Replaced flexible at discharge and intermediate pressure.

equally rated, and the only difference ought to be the length of the elbowed end. Vibrations in the order of 1X of the rotating frequency of the machine were observed, 300 rpm. No signs of rubbing against the grid of the floor were found.

The failures of corrugated braided hose frequently happen in the form of small holes or cracks. Therefore the condition of leak before break is generally most frequent, diminishing the consequences of the failure. Antecedents of unexpected failures in this kind of components have generated a recent tendency in the petrochemical industry to replace flexible by other types of elastic joints [1].

2. Inspection and evaluation of evidence

It is of significant importance the determination of the site of initiation, the form of propagation, the morphology and the direction of the fractures and their possible interaction with other surface or sub-surface defects in the materials of the flexible joint (mesh, corrugated hose and end fittings). For this purpose, qualitative visual descriptions of the different regions were made. The morphology of the failure was characterized and its interaction with some geometric and constructive characteristics was determined.

2.1. Evidence on the corrugated hose

During the failure a mainly circumferential fracture took place, near the lower sleeve. (Detail in Fig. 3). The fracture was branched along partially longitudinal cracks, forming a section that separated from the rest of the tube and is not available for its analysis. This section was probably expelled by the force of the gas during the breakage. At the end of the failure the corrugated hose was straightened, acquiring a length several times the original.

The corrugated hose presents two bands of wear on the outer lobes of the wave, due to contact with the metallic braid, this loss of material generated a local reduction of the thickness, larger than 50%. Therefore, of the initial thickness of 0.6 mm, in some sectors there was only 0.3 mm. The wear pattern is not uniform in all the surface of the corrugated, it is aligned in two longitudinal strips, these strips begin in opposite sides (approximately 180° in the perimeter in the upper end), and join

Fig. 3. Inner side of intermediate pressure hose, at the final failure place, near the lower sleeve.

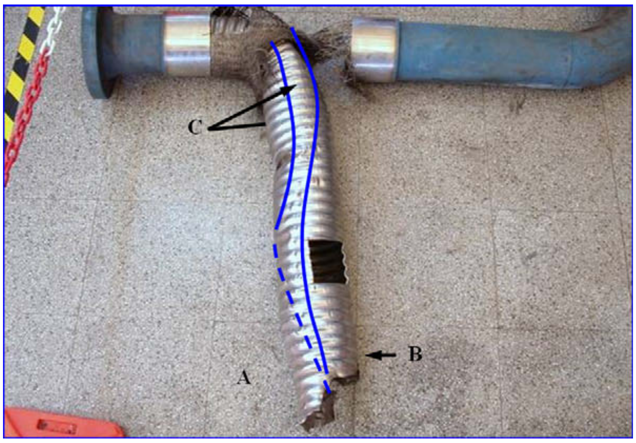

Fig. 4. Wear pattern on the corrugated, scheme of the distribution.

on the outer side of the curve in the lower end (Fig. 4). On the other hand, no contact marks can be seen on the other side of the tube at the same height (Fig. 5, see position B). At the other end, opposite to the burst site, wear is located along two opposite sidebands.

Details of each one of the two samples obtained with rubbing marks are observed in Fig. 6. The marks follow in all cases the pattern of the metal braid. The concavity that is observed in the zone with wear was produced when stretching the lobes of the corrugated.

2.2. Evidence on the braid

All the samples obtained from wires of the mesh form the zone near the lower ferrule have characteristic wear marks, made against other wires of the mesh (Fig. 7a) and against the lobes of the corrugated (Fig. 7b). All the wires in the zone of the failure of the braid have signs of wear, with a metal loss of more than 50% of their original section [2].

Electronic scanning microscope (SEM) inspection allows defining the nature of wear. The distance between wear marks agrees with the diameter of the wires (Fig. 8 – ×50). When the edges of rubbing marks were analyzed, signs of plastic deformation and striations in the direction of the wire were found (Fig. 9 – ×300). The inspection with larger magnification does not show any evidence of erosion by particles.

Inspection of the ends of the fractured wires allows determining the failure mechanisms. The analyzed samples all have the same characteristics. All they are cut in a severely worn zone, the fracture front has an area of plastic deformation and a

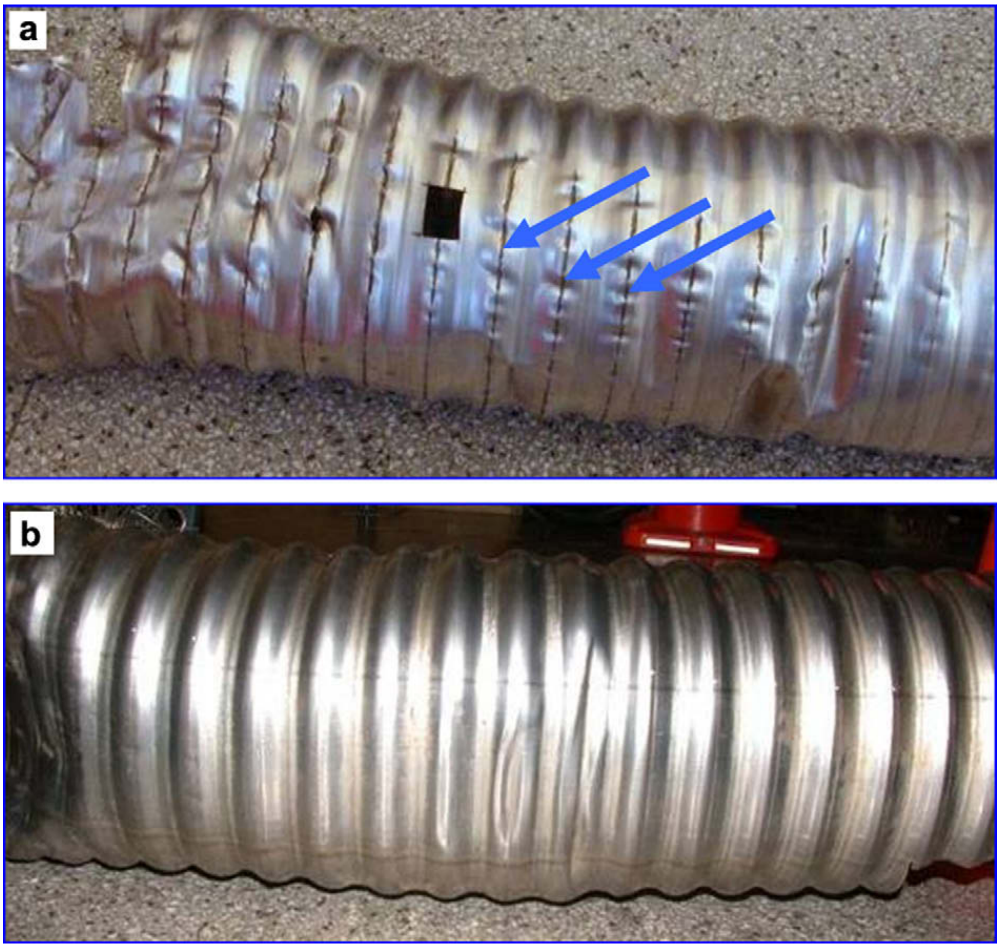

Fig. 5. Severe wear of the corrugate on de outer side of de elbow (a) and no wear marks can be seen at the opposite side (b).

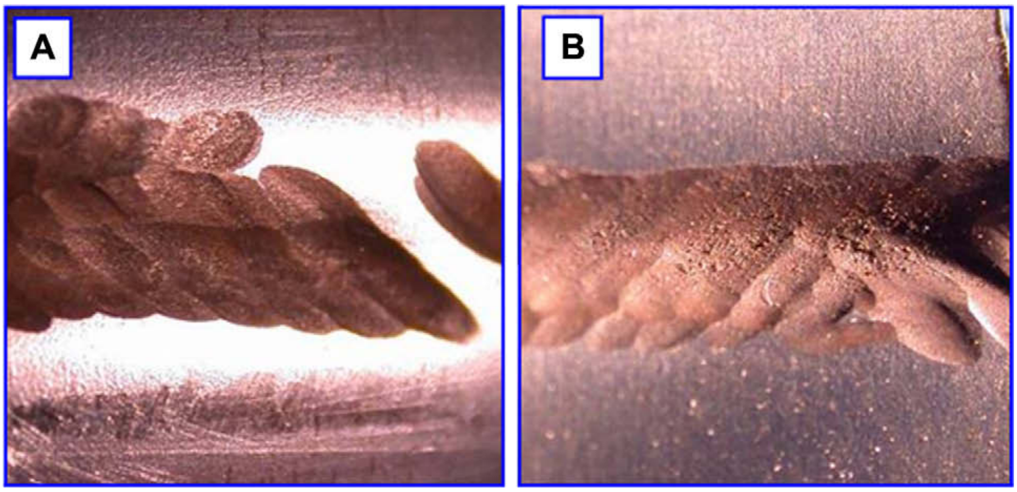

Fig. 6. Wear pattern on corrugated at the outer side of lobes (approximately ×20).

flat fracture zone (Fig. 10). Fig. 11 shows a front sight of the fracture zone on another sample. The areas present are the same in all samples.

A larger magnification of the squared zone in Fig. 11, in the front of flat fracture, shows striations characteristic of fatigue crack propagation (Fig. 12) [3]. Striation spacing is 1–2 µm, the crack advances from right to left in the figure. Near the initiation zones this spacing is reduced approximately to one fifth, so it is more difficult to appreciate. In austenitic steel, the

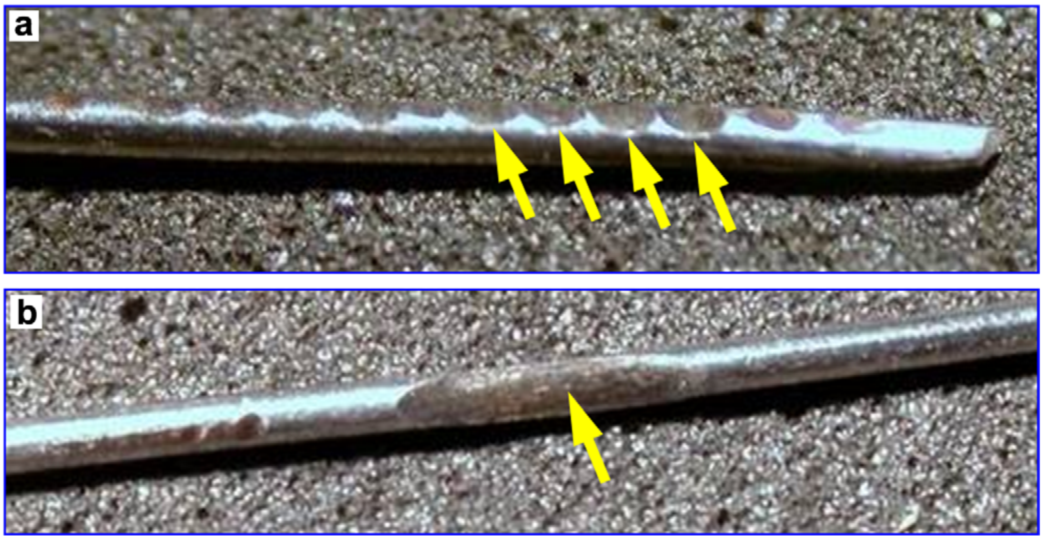

Fig. 7. Wear marks on wires produced by other wires (a) and against lobes of the corrugated (b).

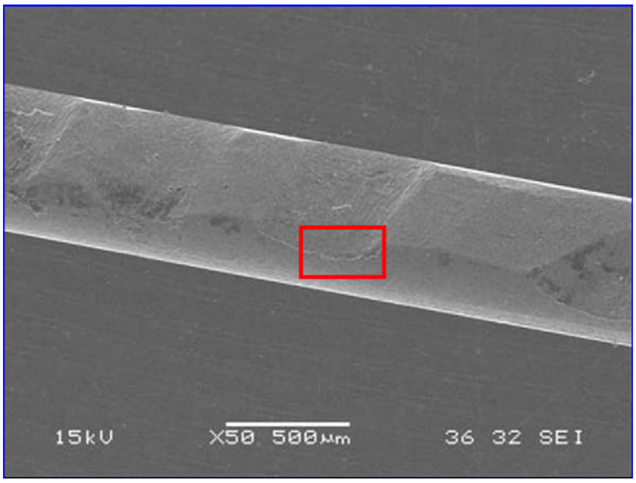

Fig. 8. Transversal striations on wires of the braid, produced by other wires (×50).

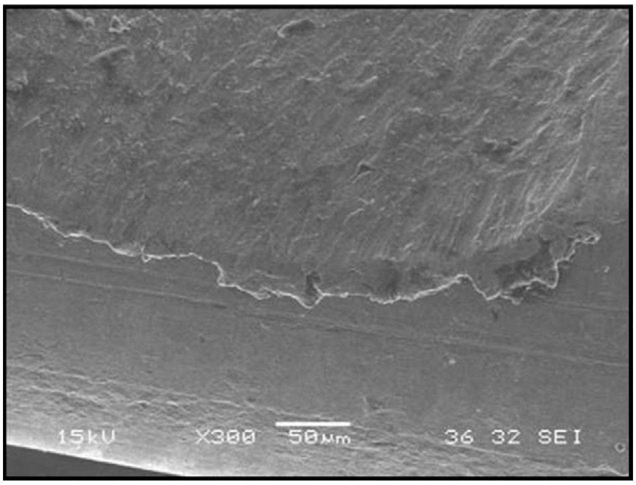

Fig. 9. Detail of Fig. 8. Plastic deformation and striation produced by other wires (×300).

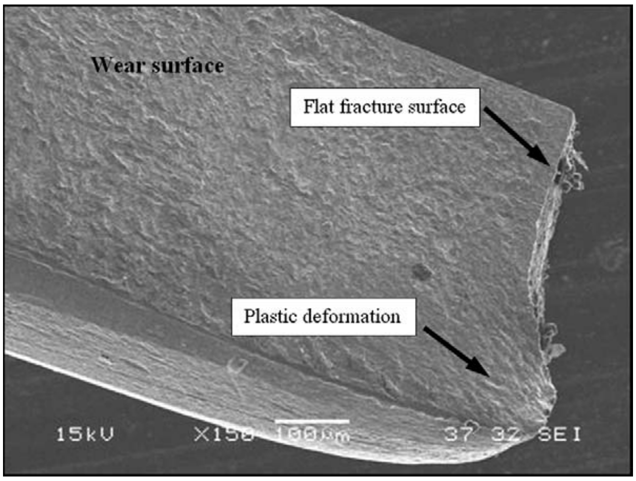

Fig. 10. Wire of the failed zone (×150).

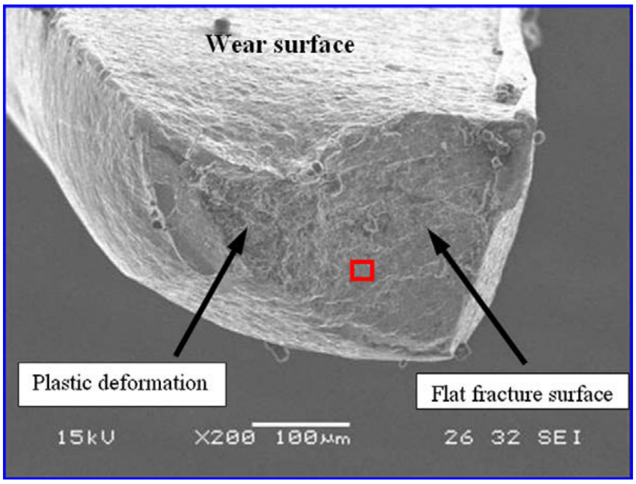

Fig. 11. Micrography of a wire tip, with the same characteristic parts as in previous samples.

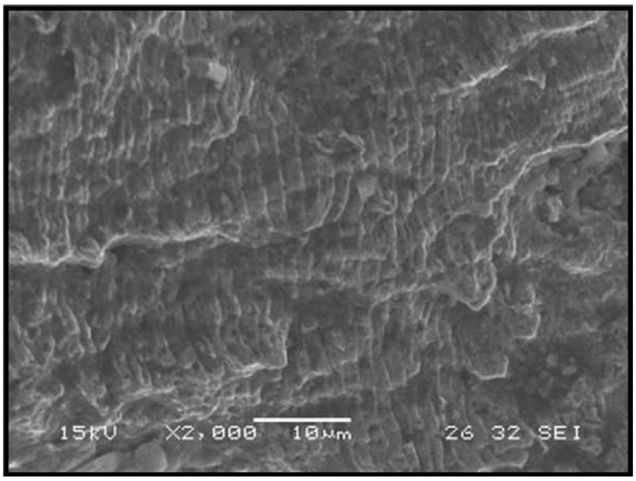

Fig. 12. Detail in Fig. 11. Fatigue propagation striations on the flat fracture surface.

fatigue propagation mechanism generates typical striation marks, indicative of the advance of the crack due to the action of in service cyclical stress [1].

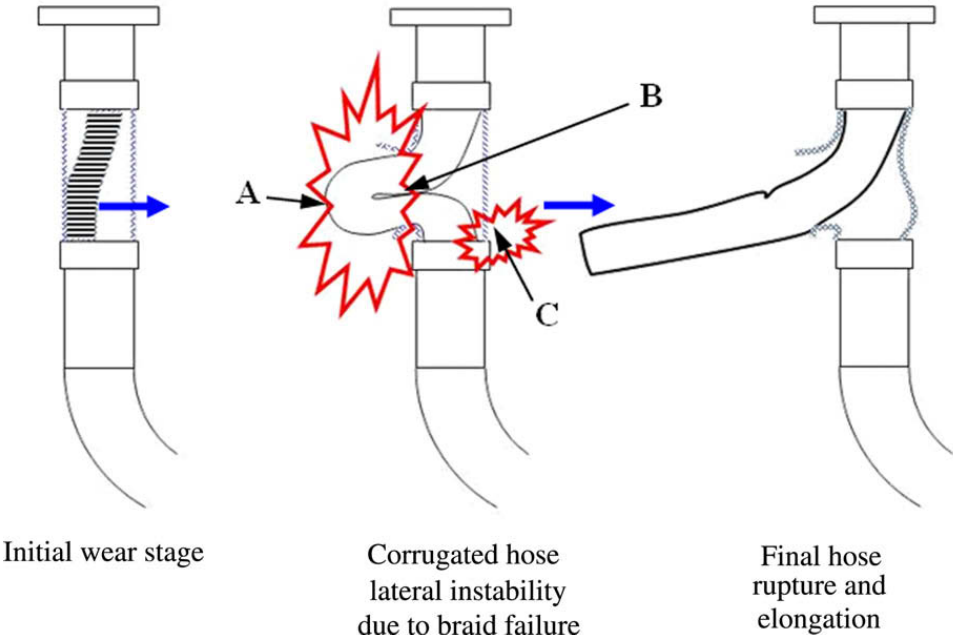

Fig. 13. Failure stages and corrugated hose deformed areas in correspondence with them.

3. Discussion of results

The failure mode can be defined as wear of the braid and the corrugated hose. Wear lead to a section reduction over 60% in some parts of the braid, so it failed by overload of the remaining ligament. The wear was produced by rubbing between the braid and the corrugated tube. This abrasion can be seen in well defined areas and unequally distributed in the perimeter of the tube, being particularly severe in zone A of Fig. 13, as detailed in the description of the wear areas. In the final instances of the failure the corrugated tube produced a squirm towards the outer side of the curve, outside the mesh that could not contain it, producing the elongation of the corrugated.

3.1. Influence of constructive aspects

The failed flexible is of a different design with respect to those used previously, it essentially differs in the design of the outer metal braid. The differences found between the failed braid and other not failed ones are summarised in Table 1. These differences are: the diameter of the wire and the amount of strands, determining a slight reduction of the net area of the mesh [3].

In flexible connections with metallic braids, the corrugated must have enough section to resist the hoop stress generated by internal pressure, but it does not oppose any rigidity to the axial loads, reason why these loads are mainly supported by the covering braid (Fig. 14).

The braid has little resistance to torsion and lateral loads, but it must have the capability to stabilize the corrugated in lateral deformation because internal pressure tends to produce lateral buckling. The critical pressure that produces this instability is a direct function of the diameter and the elastic rigidity of the corrugated, and an inverse function of the length. Depending on the geometry of the application, the wire mesh must support the axial loads generated by the internal pressure, as in an U (loop) arrangement. Imposed loads and displacements in straight flexible connections, strongly depend on the way in which the flexible is installed, and on the displacements imposed by the fittings to which the hose is connected.

A smaller equivalent area of the mesh implies a smaller resistance to longitudinal loads. This is not critical in straight flexible connections, in which the end fittings absorb axial loads, as in the case of the failed one. On the other hand, the mesh

Table 1
Differences found between of the failed braid and other.

Shell DS flexibles	Failed	Other
Diam. of wires (mm)	0.6	0.65
No. of wires	12	24
No. of strands	96	48
N, total number of wires	1344	1344
Braid angle (°)	45	45
Total area (mm^2)	325.5	382
Total equivalent axial area (mm^2)	229	270

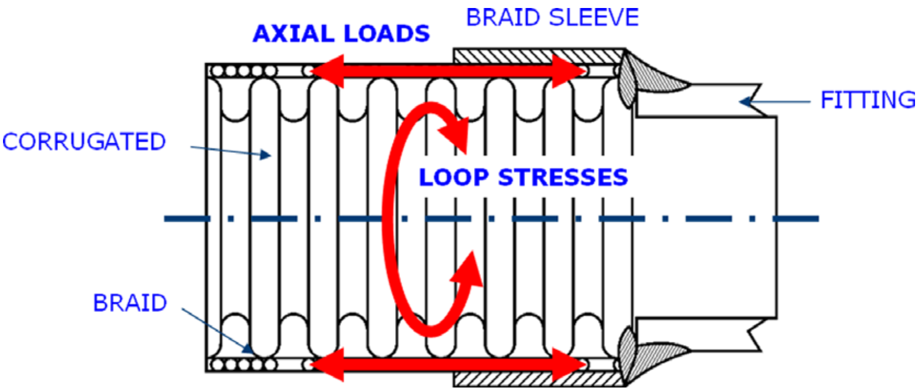

Fig. 14. Main stresses on braid and hose.

provides dumping action to the set, partly by means of the friction distributed between the wires of the mesh and partly against the wall of the corrugated, reason why both elements must act with little relative displacement to avoid wear. Wear usually is very severe when resonance conditions take place; the change of design modified the suspended mass and rigidity, reason why the natural frequency could have varied with respect to the flexible used previously.

With respect to the design pressure, the specification of the manufacturer for this diameter (6 in.), and model of flexible (corrugated with a stainless steel mesh), indicates a nominal allowable pressure P_n of 20 bar (2 MPa). The application standard ISO 10380 [1] establishes the temperature derating factor; the manufacturer's selection catalogue [4] establishes that the maximum operative pressure P_s must be equal or smaller than the maximum allowable pressure P_m.

$$P_s \leqslant P_m$$

P_m results from affecting the nominal pressure P_n by the derating factors f_t, temperature factor and f_{din}, dynamic factor

$$P_m = P_n * f_t * f_{din}$$

In this case the service temperature factor f_t is one. The dynamic factor depends on the mechanical conditions of vibrations and the characteristics of the flow and pressure of the fluid. The flexible connections were placed as a modification of the original piping design to solve to a problem of fatigue at the discharge of the propane compressor. The compressor is an alternative machine and the discharge vessels are lowering pressure pulsation. Under these conditions the dynamic factor must be taken as 0.55 or 0.4 depending whether the pressure is considered variable or pulsating (Table 2). In both cases, as the nominal pressure of operation is 13 bar, P_m is 11 bar (1.1 MPa) for $f_{din} = 0.55$. It can be seen that under normal operating conditions the internal pressure is greater than P_m. The lowering of the allowable pressure down to 55% of the nominal pressure is because fatigue in the wires of the mesh and in the corrugated tube can appear under cyclic loads. This is, indeed, the mechanism that originated the final fracture of the wires of the mesh, after wires section was locally reduced by wear.

3.2. Influence of operational conditions

On the basis of the obtained data and the fractographic analysis of the corrugated tube and the wires of the outer mesh, there is sufficient information to define the most probable mechanisms of failure and the operative conditions that lead to final failure. The nature of the fractures in the wires indicates gradual in service degradation, that is to say, they are the result of wear mechanisms and crack propagation during a reasonably prolonged time of use of the equipment. Then it can be discarded an over pressure as root cause of the failure.

The wear marks on the surface of the corrugated hose indicate that the braid was not uniformly in contact with the surface of the corrugated, only on partly of its perimeter. Throughout the flexible, the corrugated tube leaned on different places,

Table 2
Dynamic factor (f_{dyn}) values for different pressure and flow conditions.

Flow	Movement		
	Short, slow movement without vibration	Long frequent movement with vibration	Continuous rhythmic movements with vibration
Constant pressure Continuous flow	1	0.85	0.7
Variable pressure Variable flow	0.85	0.7	0.55
Oscillating pressure Alternate flow direction	0.7	0.55	0.4
Water hammer (electric valves) Sudden flow changes	0.55	0.4	0.25

as it is indicated in Fig. 4. The wire braid narrows its diameter as traction is exerted, so it is inferred that the flexible joint worked under slightly compressed condition, hold in that condition by the end fittings. Under those conditions a gap between corrugated and the braid was generated, allowing the formation of a squirm by lateral instability. It had to be stabilized by the wire by means of traction stresses of a sector of the strands, fact that matches with the distribution of the wear in the corrugated and the braid.

The generated wear gradually reduced the resistant section of the wires. The traction stresses in some wires were increasing with the reduction of section until the magnitude of the cyclical loads initiated the propagation of cracks by fatigue in some wires, scaling up the damage until the catastrophic failure. The mechanism of propagation by striations observed (Fig. 12) indicates a process of crack propagation by fatigue during period of the life of flexible previous to the failure. In materials FCC as AISI 304 each striation usually indicates the propagation of one cycle load [3].

In such case, we can consider approximately the number of required cycles to propagate the damage throughout half of the remnant diameter of a wire. Considering an average distance of 0.5 μm between striations, about 500 cycles are required to propagate a crack trough 250 μm. Considering that the frequency of cyclic loads corresponds with that of the compressor speed, it can be concluded that only a few minutes are necessary to propagate the cracks until the break condition. The owner data indicates that this flexible had been operating about six months in good condition. So it is observed that most of the in service life time was spent in the thickness reductions by fretting or inter metallic rubbing of the wires of the braid.

3.3. Root cause of the failure

Due to dimensional problems, the flexible hose worked without global traction stresses, this allowed the creation of a gap between the corrugated and the braid. This gap permitted a buckling of the corrugate, generating localized zones of contact. The squirm was stabilized by the braid in the contact places, where wear took place. The gap between the mesh and the corrugated diminished the dumping effect, allowing greater displacements, maintained by the perturbing cyclical discharge pressure of the compressor and the vibrations of the end fittings. The subsequent reduction of section of the wires of the mesh, indeed in the on traction strands, as mentioned before, increased the magnitude of the cyclic stress until the initiation and fatigue propagation of cracks in many wires, scaling up the damage until the catastrophic failure.

4. Conclusions

- The failure of the flexible took place by overload of the braid, after a noticeable local reduction of section of the wires, caused by wear. The wear was caused by in service rubbing between the wires and the corrugated.
- In the final steps of the failure the corrugated produced a squirm outside the braid towards the outer side of the curve, producing the stretching of the corrugated hose. The final burst of the corrugated took place by traction, increased its instability by the burst of the wires.
- The fractures in the wires were consequence of fatigue crack propagation in previously worn areas; overpressure can be discarded as cause of the failure.
- There were no fabrication defects in the wires, the results of mechanical and chemical tests agree with the specifications.
- The flexible connection has a working pressure larger than the maximum allowable pressure P_m defined by the manufacturer's catalogue, for the cyclic pressure conditions at the discharge of the compressor.
- The flexible worked in its position supported by the end fitting. Due to dimensional facts, once set in working position, was free of global traction stresses. This allowed the generation of a gap between the corrugated and the braid. Lower rigidity of the braid contributed to easy installation between flanges.
- The braid was not evenly in contact with the surface of the corrugated, only partly of its perimeter, due to a squirm allowed by a gap between de hose and the braid.
- The change of geometry of the braid has modified its dynamic characteristics; this could help to the occurrence of larger relative displacements.
- Recommendations are made to establish procedures to verify dimensions previous to montage and to increase the inspection frequency of these elements, as well as to verify the vibrations level of the connected machines.
- Due to the greater reliability shown by the previous design, it would be possible to return to it, but even so they it be under dimensioned. A double braided flexible would fit calculus recommendation due to its larger nominal allowable pressure P_n. Elastomer material placed between corrugated and braid would diminish wear caused by vibrations.

Acknowledgements

This research work was funded by CONICET (Consejo Nacional de Investigaciones Cientıficas y Tecnicas) from Republica Argentina. Thanks are given to Shell and GIE S.A. (Argentina) for technical and financial support and for permitting publication of proprietary information.

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