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Life Prediction of High Pressure Hydraulic Hose Assemblies by the Impulse Test

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Flexible hydraulic hose assembly that consists of hose and joints is used widely on various construction heavy equipments, agricultural machines, motor vehicles, and industrial heavy machines that require flexibility on hydraulic pipelines. It is classified by the maximum usage pressure which is determined by the winding layers of coiling steel wire and the inner diameter of the hoses. In this paper, we designed and performed an accelerated life test for assessing the reliability of a flexible hydraulic hose assembly. In the proposed accelerated life test, typical impulse pressure testing method is applied with the half omega flexing operation to simulate the practical flexing motion of the hose assembly.

Keywords : *hydraulic hose, fitting, impulse test, accelerated life test, weibull distribution*

Notations

P_a : Zero-to-Maximum amplitude of pressure cycle
N : Cycles to failure at pressure amplitude P_a
P_b : Burst pressure (one cycle life)
s : Slope of curve on log-log plot
n : Power index
β : Shape parameter of the Weibull distribution

1. Introduction

The assembly of hydraulic hose having a part that requires flexibility on hydraulic pipe line is used widely on various equipments such as construction heavy equipments, agricultural machines, vehicles and industrial machines etc. It consists of hose and joints and is classified by the maximum usage pressure. The number of the winding layers of coil steel wire, that is to increase the internal pressure limit and the inner diameter of the hose determine the maximum usage pressure of the hose assembly.

As the related control technology develops, various kinds of three dimensional motions of hydraulic devices become possible and it increases the need for and use of the flexible hydraulic hoses.

Due to the extremely high pressure applied and the repetitive motions of bending and stretching, failures of hose assembly such as leakage and burst tend to be increasing proportionally. The failures of hydraulic hose assembly may cause the shutdown of the entire hydraulic system. For the reliable operation of the entire hydraulic system, it is important to replace the hydraulic hoses before they break down. By predicting the lifetime of a hydraulic hose assembly, we can determine appropriate replacement policy for the hose assembly.

Berns and Lobmeyer(1986) performed a repetitive impulse test by using higher impulse pressure than the practical pressure of a hydraulic hose and from the test results, they proposed a cumulative damage model for the assembly of hydraulic hose.

SAE classifies the impulse pressure testing method for hydraulic hoses by types of hoses from SAE R1 to R17 and uses the testing method for the life prediction of hydraulic hoses. However, the impulse pressure testing method doesn't consider the practical condition of flexing operation. In addition, since only 4 hoses are tested, we may not have sufficient failure data for the prediction of lifetime distribution of a hydraulic hose.

In this paper, potential failures of hydraulic hose assemblies were analysed and effective test items are determined through 2-stage quality function deployment. And an accelerated life test that considers the practical flexing operation is designed, performed and analysed based on the existing impulse pressure testing method.

1.1 Structure of hydraulic hose assembly

A hydraulic hose consists of the inside rubber layer, the steel wire layer and the outside rubber layer. The steel wire layer consists of the bending and stretching of a rated hose. A hose such as steel wire reinforced and multiple spiral steel wire reinforced consists of the assembly of fitting as a part of swaging. Fig. 1 shows typical structure and components of hose assembly.

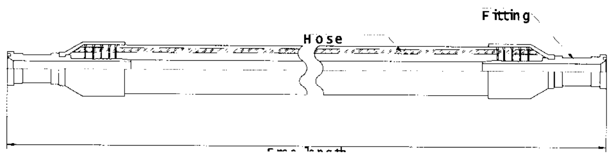

Fig. 1. Typical hydraulic hose assembly

1.2 Pressure wave shape and frequency of impulse testing

A pressure wave shape of impulse testing defines as a square wave shape in Fig. 2 on SAE J 343 and ISO 8032. The range of period is from 0.5Hz to 1.25Hz.

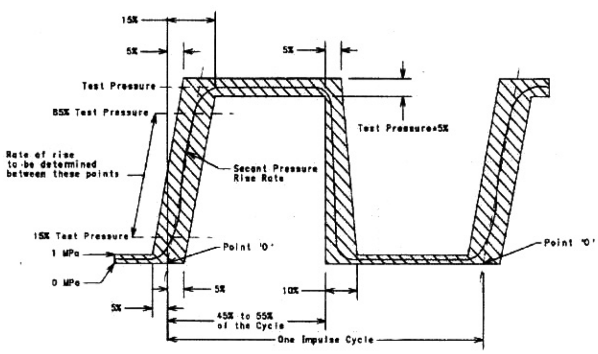

Fig. 2. Impulse pressure wave pattern

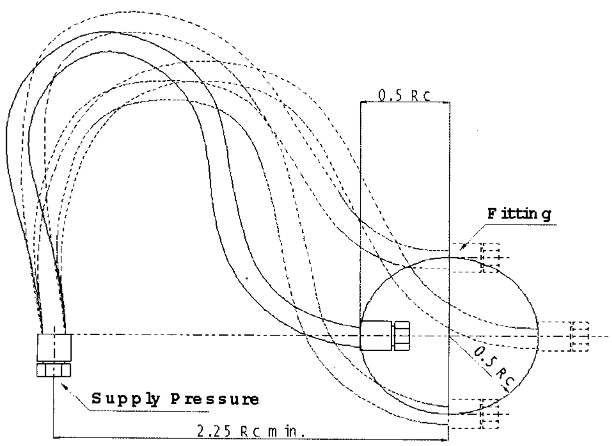

Fig. 3. Half omega flexing

Futhermore, to simulate various types of repetitive bending and stretching operations, half-omega flexing motion as shown in Fig. 3 is applied during the test.

2. Testing items and cumulative damage theory

2.1 Testing items of hydraulic hose assembly

The failure mode and mechanism analysis and criticality matrix analysis were performed to assess the relative importance of failure modes. From the two-stage quality function deployment, effective testing items are chosen.

2.1.1 Analysis of failure mode and mechanism

Main functions of hydraulic hose assemblies are connection with counterparts, pressure maintenance, hydraulic transport, and flexible operation. Most types of failure appear as a leakage. Failure mechanisms of the hose assembly are shown in Table 1.

Table 1. Failure mode & mechanism analysis

Components	Function	Failure mode	Failure mechanism and causes	
Fitting	Connect and Pressure maintenance	Leakage	1-1	overstress fracture
			1-2	external corrosion
			1-3	cyclic pressure fatigue cracking
Hose	Pressure maintenance hydraulic transport & flexibility	Leakage	2-1	excessive pressure and blowout
			2-2	thermal aging and cracking
			2-3	chemical degradation from contamination
			2-4	degradation from lubricant incompatibility
			2-5	fatigue with vibration
			2-6	external wear of braiding and tube
			2-7	cyclic pressure fatigue cracking

2.2.2 Criticality matrix analysis

Table 2 represents the results of criticality matrix analysis. It provides major failure modes and mechanisms.

Table 2. Criticality matrix analysis

Severity		Low		Midium		High	
High	Ⅲ		Ⅱ	1-1, 2-1, 2-3 2-5, 2-7		Ⅰ	
Midium	Ⅳ		Ⅲ	1-2, 1-3 2-2, 2-4		Ⅱ	2-6
Low	Ⅴ		Ⅳ			Ⅲ	

failure frequency

Table 3. Failure mode effects & criticality analysis

Com-ponents	Failure Mode	Failure mechanism and causes	Effects	Evaluation		
				Frequency	Severity	Criticality
Fitting	Lea-kage	overstress fracture	Pressure loss and system damage	2	3	7
		external corrosion	Leakage and inability to couple or uncouple	2	2	5
		cyclic pressure fatigue cracking	Pressure loss	2	2	5
Hydraulic Hose	Lea-kage	excessive pressure and blowout	Pressure loss and system damage	2	3	7
		chemical degradation from contamination	Pressure loss and system damage	2	2	5
		thermal aging and cracking	Leakage and pressure loss	2	3	7
		degradation from lubricant incompatibility	Leakage and pressure loss	2	2	5
		fatigue with vibration	Leakage and pressure loss	2	3	7
		external wear of braiding and tube	Leakage and pressure loss	3	2	7
		cyclic pressure fatigue cracking	Pressure loss and system damage	2	3	7

Most importance ◎(9), Importance ○(5), commonness

Table 4. Quality function deployment level 1

Component	Fitting			Hose						
Failure Mode / Requir-ement	Overstress too long test	external corrosion	cyclic pressure fatigue cracking	over pressure or inadequate spec	thermal aging and cracking	chemical degradation	degradation from lubricant incompatibi lity	fatigue with vibration	external wear of braiding and tube	cyclic pressure fatigue cracking
cyclic pressure durability	○		◎	○						◎
dimensional stability				◎		△	△			
tight bending radius				○						○
oil compati bility				△		◎	◎			
extended operational life	△	○	◎	△	◎	△	△	◎	◎	◎
severe envir onmental durability		◎	○	○	◎	△	△	◎		○
high strength tubing				◎	◎	○	○	○		◎
wear resistance braiding									◎	
easy connect/ disconnect		◎								
Minimum leakage	◎	○	◎	◎	◎	○	○	◎	◎	◎
Scores	17	28	32	48	36	28	28	32	27	46

2.2.3 Failure mode effects and criticality analysis

Results of criticality analysis for each failure mode are given in Table 3.

2.2.4 2-stage quality function deployment

First, the relationships between requirements (or specifications) and failure modes are analysed and the results are given in Table 4.

Next, the relationships between failure mechanisms of major components and testing items are assessed. The results are given in Table 5 and it reveals that major testing items of hydraulic hose assemblies are impulse test, burst test, and proof test.

2.2 Cumulative damage theory of hydraulic hose assembly

It is possible to increase the number of cycles to verify the cumulative damage of a hydraulic hose assembly.

The relationship curve between cumulative damage and life cycle by impulse pressure(P-N curve) is similar to S-N curve. The equation is as follows:

$$P_a = P_b(N)^s$$

$$N = \left(\frac{P_a}{P_b}\right)^{\frac{1}{s}} = \left(\frac{P_b}{P_a}\right)^n, \quad (1)$$

$$s = \frac{\log(Pa/Pb)}{\log N}, \quad n = -\frac{1}{s}.$$

If a hose assembly bursts immediately at maximum working pressure of 400 percent and it fails at 5×10^5 cycle when 125 percent pressure is applied, the life(cycle) of the assembly at use condition(practical working pressure) is calculated as follows:

$$400 = P_b(1)^s, \quad P_b = 400, \quad (2)$$

$$125 = 400(500000)^s,$$

$$s = \frac{\log(125/400)}{\log(500000)} = -0.08863 \quad (3)$$

$$n = -\frac{1}{(-0.08863)} = 11.281739$$

In the above equations, n indicates the accelerated life index of a hydraulic hose. Life(cycle) of the hose assembly at use condition of 100 percent pressure is obtained by

$$N_{100} = (400/100)^{11.281739} \fallingdotseq 6.2\times10^6 \ cycle. \quad (4)$$

Table 5. Quality function deployment level 2

Component	Failure mechanism		Proof test	Change in length test	Burst test	Cold bend test	Ozone resistance test	Impulse test
Fitting	Overstress too long test	17	◎		◎			◎
	external corrosion	28					△	
	cyclic pressure durability	35	○		○			◎
Hydraulic Hose	over pressure or inadequate spec	48	◎	○	◎	◎		△
	thermal aging and cracking	36	△	△	△	△		○
	Chemical degradation	28		△			○	
	degradation from lubricant incompatibility	28	△	△	△	△	○	△
	fatigue with vibration	32		△	△	△		○
	external wear of braiding and tube	27						○
	cyclic pressure fatigue cracking	46	○	△	○	△		◎
Test Effectiveness Score			1182	750	1278	858	364	1585
			3	5	2	4	6	1

Most importance ◎(9), Importance ○(5), commonness △(3)

Life(cycle) of the hose assembly at 133 percent and 200 percent are respectively calculated by

$$N_{133} = (400/133)^{11.281739} \fallingdotseq 2.5\times10^5 \ cycle$$
$$N_{200} = (400/200)^{11.281739} \fallingdotseq 2.5\times10^3 \ cycle. \quad (5)$$

From the above results, we can see that acceleration factor of impulse testing pressures of 133 percent and 200 percent are 25 and 2500 respectively.

3. Analysis of testing results

3.1 Burst pressure testing of a hydraulic hose

The burst pressure of a hydraulic hose assembly is set to above 400 percent (SAE J 517), and we employed a superhigh pressure intensifier of a double rod furnishing over 300MPa as shown in Fig. 5.

Since the pressure increase rate affects both the burst limit of a test item and pressure measurement, we adjust the pressure test equipment to raise pressure up to 400% in 60 seconds. Multi Data Acquisition Software of Parker electronics and 400 MPa pressure Transducer of NTS are used to measure the instantaneous burst pressure.

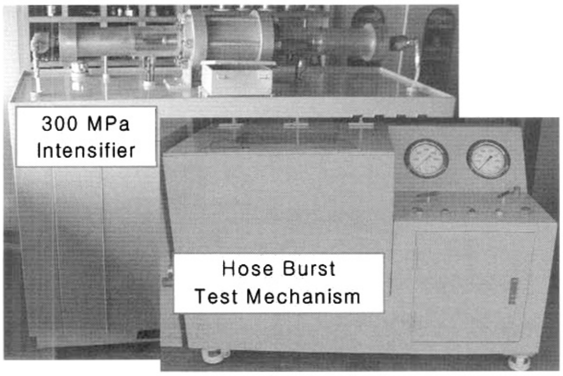

Fig. 4. Hose burst tester

3.2 Burst pressure testing of hydraulic hose

Fig. 5 shows burst test results of four specimens. Specimens with 600 mm long, 25 mm inside diameterand 35 MPa maximum working pressure were loaded one by one on the testing instrument. The bursting impulse pressure was measured as in Fig. 6.

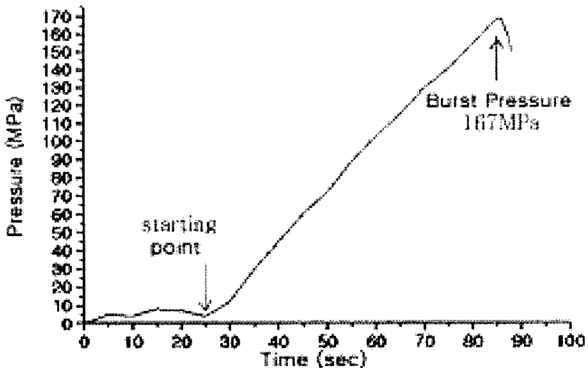

Fig. 5. Burst test result

Table 6. Burst test result & Pressure ratio

No	Burst pressure (MPa)	Burst pressure/ max. Press.×100
1	167	481 %
2	170	486 %
3	163	465 %
4	159	454 %

Table 6 shows the ratio of the burst pressure and maximum working pressure. The ratio of the average burst pressure was 471.5 percent.

3.3 Impulse pressure testing of hydraulic hoses

Applying a square impulse wave shape pressure in Fig. 2 and half omega flexing operation in Fig. 3, we tested 7 hose assemblies at the maximum pressure condition of 200 percent (70 MPa) and 168 percent (58.8 MPa) respectively.

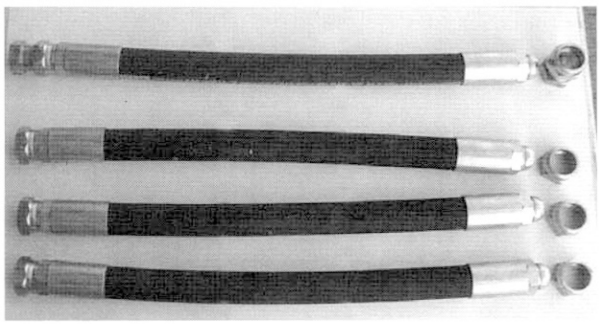

Fig. 6. Burst test hose

The test continued until all of the test specimens burst. With the fixed pressure of 133 percent (46 MPa), we tested 14 specimens. The pressure period and flexing period were 0.75Hz and 0.5Hz respectively.

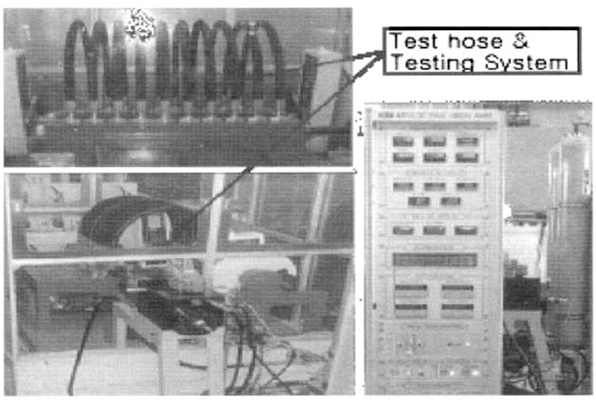

Fig. 7. Hydraulic impulse testing system

3.4 Testing result of hydraulic hoses

Table 7 shows results obtained from the accelerated testing condition in the section 3.3. Fig. 8 shows a photograph of bursted hoses.

3.5 Testing result analysis of hydraulic hoses

Fig. 9 shows goodness of fits for various lifetime distributions and the results indicate that Weibull distribution fits best. So we conclude that the lifetime of the hydraulic hose assembly follows a Weibull distribution.

Fig. 10 shows the probability density function, reliability function, and failure rate function of the Weibull lifetime distribution of the hose assembly. The shape parameter of the Weibull distribution (β) are estimated as $\beta = 2.3904$ at 133 percent of the impulse pressure, $\beta = 4.8470$ at 168 percent, and $\beta = 10.423$ at 200 percent. Fig. 11 shows the inverse power law life-stress relationship. It seems that inverse power law relationship is appropriate for the accelerated test data of Table 7.

Fig. 12 shows the predicted lifetime distribution at working(use) condition. The 95% confidence interval of MTTF(Mean Time To Failure) is (2.0×10^6 cycles, 3.9×10^6 cycles) and the value of the common shape parameter estimated under the inverse power law relationship is $\beta = 3.36215$.

Table 7. Impulse test result

No	200% press	168% press	133%(1) press	133%(2) press
1	11,330	16,500	54,500	169,800
2	11,520	51,000	115,400	260,200
3	12,060	55,000	115,400	264,080
4	12,380	57,000	235,000	288,100
5	13,040	59,000	276,800	407,990
6	14,670	63,500	381,640	414,090
7	14,720	63,500	438,400	447,200
mean cycle	12,817.14	52,214	231,020	321,637

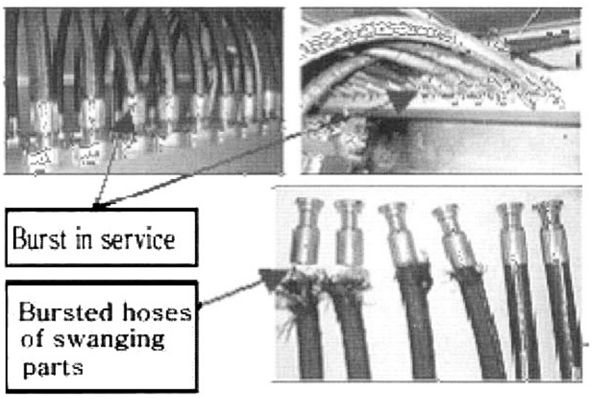

Fig. 8. Bursted hose impulse test

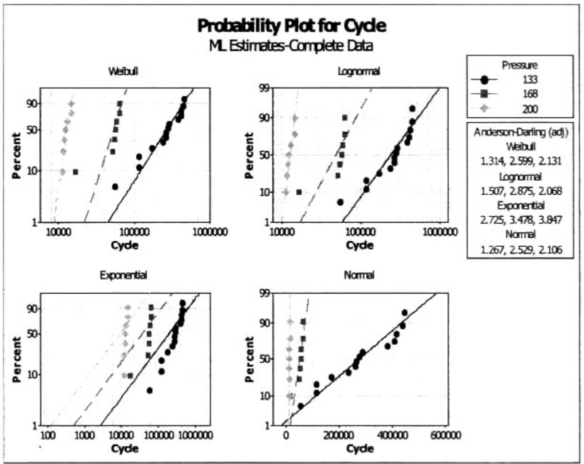

Fig. 9. Goodness of fit for various distribution

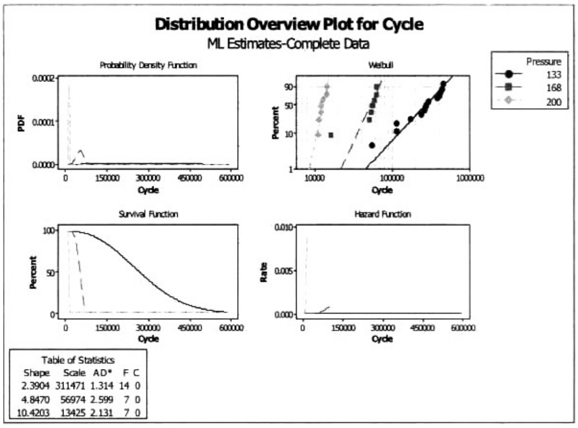

Fig. 10. Distribution overview plot

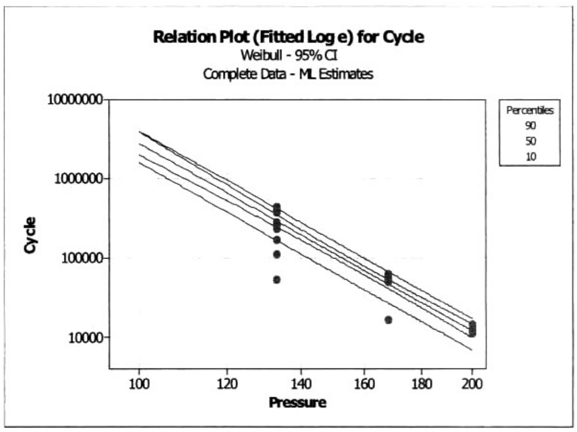

Fig. 11. Inverse power law elation between pressure and life(cycle)

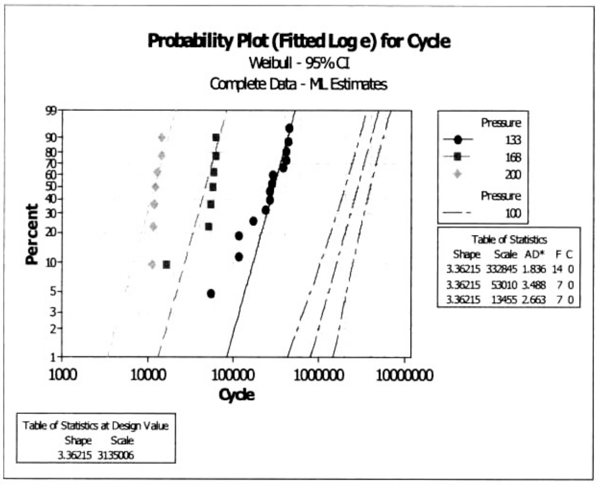

Fig. 12. Life prediction at use condition of 100% pressure

4. Conclusions

In this paper, the failure mode and mechanism analysis, criticality matrix analysis, and failure mode, effects and criticality analysis were performed to investigate and assess the potential failure modes of the hydraulic hose assembly. The priority of testing items was determined quantitatively using the two-stage quality function deployments.

We could see that the major failures of hydraulic hose assemblies were bursts of hoses and separations of hoses from the swaging parts that connect hoses to the counterparts.

Accelerated life test data indicate that the lifetime of the hydraulic hose assemblies follows a Weibull distribution but the values of shape parameters may vary according to the applied impulse pressure. The common shape parameter under the inverse power law relationship was $\beta = 3.36215$ and the 95% confidence interval of MTTF(Mean Time To Failure) was (2.0×10^6 cycles, 3.9×10^6cycles).

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