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PRESSURE REVERSAL STUDY THROUGH TENSILE TESTS

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ABSTRACT

This paper is a summary of the results from a study of the variables related to pressure reversal and was sponsored by the U.S. Department of Transportation, Office of Pipeline Safety. The circumferential pipe stress, which is the most significant variable in pressure reversal, was examined by using tensile specimens and then relating the results to pressurized pipe. A model is proposed that gives some insight into how pressure reversal can be minimized when a section of pipe is being hydrotested. Twenty tensile specimens from X-42 electric resistance welded (ERW) pipe and twenty specimens from X-52 ERW pipe were tested. Each specimen had a machined flaw. The flaw regions were monitored using strain gages and photoelasticity. These tensile tests represent the first phase of a research effort to examine and understand the variables related to pressure reversal. The second phase of this effort will be with pipe specimens and presently is in progress.

INTRODUCTION

When pipe lines are hydrostatically tested in the field to check for leaks and to prove the system for safe operation at the design pressure, some pipe failure peculiarities have been noted and are cause for concern. In some instances when hydrostatically qualifying a section of pipeline, a failure has occurred and when the hydrostatic test is continued after the needed repair another failure occurs at another point in the pipeline section but at a lower pressure than was achieved earlier. The concern is that hydrostatic testing may in some instances cause damage to the pipeline at the same time the line is being proof tested. This phenomena is called pressure reversal and is defined as

$$P.R. = (\sigma_p - \sigma_f)(100/\sigma_p)$$

where,

$P.R.$ = pressure reversal in per cent,
σ_p = the previous maximum proof stress (or pressure), and
σ_f = the failure stress (or pressure).

Because of the concerns associated with this phenomena, the Office of Pipeline Safety is sponsoring a research effort at the Oak Ridge National Laboratory to investigate pressure reversal. The experimental work under this project was divided into two parts:

DISCLAIMER

Part I consisted of examining variables related to pressure reversal by testing tensile specimens and Part II (in progress) will add to the data base of Part I by testing pressurized pipe specimens. The results from Part I are the basis for this paper.

In a fundamental study of any kind it is important to be able to control the contributing variables. The use of tensile specimens for this part of the investigation allowed for close control of the variables contributing to pressure reversal and as a consequence data were obtained to help examine the fundamentals of this phenomena.

Correlation of the uniaxial stress data from the tensile tests to the biaxial stress field of a pressurized pipe was accomplished by matching the maximum principal strains. The rationale for matching maximum principal strains rather than maximum principal stresses is because material failure directly relates to the amount of deformation at a point and, thus, deformation is the preferred variable. To illustrate the validity of this rationale, the maximum principal strain from a tensile specimen containing a machined flaw was used to predict the failure pressure of a capped end pipe specimen with the same size machined flaw and of the same material. The predicted failure pressure was 2900 psi and compared well with the actual failure pressure in the pipe specimen at 2923 psi. This close correlation between the tensile specimens and pressurized pipe, allows what was learned about pressure reversal from the tensile tests to be directly related to pressure reversal in pipe.

TEST SET UP

A sketch of the tensile specimens selected for this investigation is shown in Fig.1. A photoelastic model of the test specimens was examined to insure that the strain field in the central region of the specimens was not distorted due to the high strains at the load pins. The tensile specimens were all made from flattened pipe material. Ten of the specimens were from X-42 plate material, ten of the specimens were from X-42 material with the ERW seam forming the central cross section, ten of the specimens were from X-52 plate material, and ten of the specimens were from X-52 material with the ERW seam forming the central cross section. A flaw as shown in Fig.1 was machined in each specimen with an electronic discharge machine.

Most, if not all, of the field observed pressure reversals have initiated with a longitudinal flaw in the weld seam of the pipe. It was reasoned that these flaws were the result of improper bonding at the seam. Therefore, to simulate these improper bonding flaws, a machined flaw rather than a stress induced crack, which leaves an unknown residual stress field, was specified for these tests.

Each of the tensile specimens was instrumented with strain gages. Each specimen had three and sometimes four gages for monitoring the strain as the models were tested. The gage locations in each model were not always the same, as gages were placed at different locations to find the points on the model that would be most helpful in monitoring pressure reversal. Figure 1 illustrates the different locations and alignments of the single element strain gages. A photoelastic coating was applied to the back surface of one of the specimens to evaluate the strain distribution in the vicinity of the flaw.

One of the first observations from these tests was that, as tensile load was applied, the strain on the back side of the specimen and opposite to the surface flaw indicated compression. The significance of this is that, in addition to the circumferential (hoop) stress reacting with a flaw, a moment develops which produces 'bending' strains in the flaw region. For an outer surface flaw, the bending strains are tensile at the root of the flaw and add with the hoop strains. Therefore, because of the large strains at the flaw root, a flaw will always progress through the pipe wall before extending in length. The strains at the root of an inner flaw subtract and do not offer the same problems that outer flaws do. The compressive back surface strain reversed and went positive as more and more load was applied and reflects a decrease in the moment effect due to necking of the matertial on the back surface, which decreases the moment arm.

Properties for the two pipe materials were evaluated and are summarized in Table I.

TEST RESULTS

To help coordinate the large amount of data from these tests, a model for pressure reversal is proposed and presented through this paper. The information shown in Tables II and III has been derived from the test data. It is emphasized that there are several variables that effect pressure reversal and if interpretations of the information shown in the tables are made without taking into account which variables were changed for each test, erroneous conclusions could be formed. To help transform the information shown in the tables to pressurized pipe, after each stress entry from the tensile tests, an equivalent pipe pressure is given. The equivalent pipe pressures were based on a pipe with a 16 inch diameter, an 0.375 inch wall, and capped ends.

DISCUSSION OF RESULTS

The proposed model for pressure reversal includes <u>two</u> different failure stresses and a <u>damage zone</u>.

The first failure stress, $\sigma f1$, is defined as the stress at failure due to a <u>continually increasing load</u>. This failure stress is quantified by taking the tensile load at failure and dividing by the gross cross sectional area of the test section. The flaw area was not used in this designation since in a pipeline application the flaw area is usually unknown. The failure stress at constant load rate depends on the material and the flaw size but is independent of time as is evident from the test times for Specimens 12, 16, 17, and 20 of Table II. There was some evidence that $\sigma f1$ can be increased by a small amount of strain hardening. The evidence for this was seen when a larger failure stress at constant load rate was seen after some specimens had been cycle loaded a few times.

The second failure stress, $\sigma f2$, is more general than $\sigma f1$. The magnitude of $\sigma f2$ changes as it depends on the time duration of the applied load, it depends on $\sigma f1$, it depends on the initial flaw size, it depends on the material properties in the vicinity of the flaw, and it depends on flaw depth extension from applied loads. Pressure reversal is a direct function of this failure stress. Because $\sigma f2$ depends on several variables, it is generally lower than $\sigma f1$, and some amount of pressure reversal is always possible. The closer $\sigma f2$ is to $\sigma f1$ the less time will be required for failure.

It is easy to appreciate that the second failure stress, $\sigma f2$, is not always a factor. For example, if the applied load is small enough a given specimen will not fail regardless of how long the load is applied. A special value for the second failure stress is identified as $\sigma f2min$ and is the smallest stress that in time will cause failure. A stress that is in the damage zone is a stress that is between $\sigma f2min$ and $\sigma f1$. While the stress is in the damage zone, two things happen, the depth of the flaw is increased and there is necking on the inside of the pipe in the flaw region. Both of these factors contribute to pressure reversal and either factor alone could initiate pressure reversal. If the stress is maintained in the damage zone long enough, failure will occur. If the stress in the damage zone is removed before failure occurs, the flaw damage stops. If subsequent loadings take and hold the stresses into the damage zone, pressure reversal will occur.

Each time the stress is taken into the damage zone and released before failure the magnitude of $\sigma f2min$ is lowered and will continue with each damage zone stress until the depth of the flaw extends through the pipe wall. Specimens 18 and 46 of Tables II and III had flaws that were extended essentially through the wall prior to failure. This indicates that $\sigma f2min$ can be reduced only so much; thus, the idea of a potential 100% pressure reversal is not realistic. The numbers would be incorrect but, for comparison purposes, one could find $\sigma f1$ for a given size flaw from the failure equation given by Maxey, et al, [1] and find $\sigma f2min$ as the failure stress for a through crack in an infinite plate by fracture mechanics. These values could be used to calculate a maximum potential pressure reversal for a given initial flaw size. Calculating potential pressure reversal in this way indicates that larger pressure reversals occur in shallow and long flaws than in shorter deeper flaws.

Specimens 46,48, and 50 of Table III indicate that load cycling below the damage zone will not effect the flaw region and that only when the stress is in the damage zone does $\sigma f2$ exist.

PRESSURE REVERSAL IN PIPE

Referencing the proposed pressure reversal model, the things necessary for a pressure reversal in a pipeline section being hydrotested are:

- The existence of two or more flaws that have failure stresses, $\sigma f1$, in the same neighborhood,

- As the pipeline section is pressurized into the damage zone of the flaws, one of the flaws will fail first and release the test pressure. The other flaw has been damaged by flaw depth extension and necking but did not fail due to the release of pressure, and

- After the pipeline section is repaired and the hydrotest resumed, the pipeline section again fails, but, at a lower test pressure than before because the second failure stress, $\sigma f2$, now controls and initiates failure before the first failure stress, $\sigma f1$, is realized. Pipeline failure records indicate that if several repairs are necessary during a given hydrotest, a pressure reversal is more likely to occur. The proposed pressure reversal model accounts for this as every load cycle that goes into the damage zone of a flaw before it fails will increase the size of the damage zone by lowering the value of $\sigma f2min$.

The potential for pressure reversal from hydrotesting a pipeline is always present. How to manage the hydrotest to minimize or avoid this pressure reversal potential is a very important consideration in the safe operation of any pipeline. Only two things can be managed in a hydrotest, the test pressure and the holding time. Testing a pipeline at pressures above the operating pressure is necessary to help remove unwanted defects. How long the test pressure should be maintained in a hydrotest has produced different views. The data from the tests conducted in this program indicate that long hold times, also, help remove unwanted defects. How long a hold time is needed is being addressed but defining a number at this time would be premature until all of the data are collected and evaluated.

REFERENCES

[1]. W.A. Maxey, J.F. Kiefner, R.J. Eiber, and A.R. Duffy, "Ductile Fracture Initiation, Propagation, and Arrest in Cylindrical Vessels", The Fifth National Symposium On Fracture Mechanics, University of Illinois, 1971.

TABLE I: MATERIAL PROPERTIES

Property Description	X-42 Plate Mtl	X-42 ERW Mtl	X-52 Plate Mtl	X-52 ERW Mtl
Stress at 0.5% Strain	53.3 ksi	-	62.7 ksi	68.1 ksi
Stress at 0.2% OffSet	51.7 ksi	-	61.0 ksi	66.1 ksi
Ultimate Stress	76.3 ksi	78.0 ksi	72.3 ksi	76.1 ksi
2/3 UpperShelf Charpy	32.7 ft-lb	34.8 ft-lb	129.1 ft-lb	119.3 ft-lb

TABLE II: DATA SUMMARY FOR X-42 TENSILE SPECIMENS

Test No.	Mid-Cross Sec. Mtl	No. of Load Cyc.	Total Test Time, Hrs.	Max. Stress Load psi	Equiv. Max. Pipe Press. psi	Failure Stress $\sigma f2$ psi	Equiv. Pipe Fail. Press. psi	Time With Fail. Load, Hrs.	Pressure Reversal %
1	Plt	8	54.15	49700	2728	47800	2624	0.55	5.1
2	Plt	1	1.41	50600	2777	50600	2777	----	---
3	Plt	1	150.00	47800	2624	47800	2624	3.42	---
4	Plt	1	1.07	50900	2794	50900	2794	----	---
5	Plt	8	108.30	50700	2783	48100	2640	9.13	5.1
7	Plt	1	1.53	49800	2733	49800	2733	----	---
8	Plt	9	83.39	51000	2799	48000	2635	30.18	6.0
9	Plt	2	3.52	50500	2772	48800	2679	0.81	3.4
11	ERW	1	21.85	48500	2662	48500	2662	----	---
12	ERW	1	1.67	53300	2926	53300	2926	----	---
14	ERW	7	28.61	54000	2964	50900	2794	2.42	5.7
15	ERW	9	52.13	52200	2865	49600	2722	0.06	5.0
16	ERW	1	1.09	51300	2816	51300	2816	----	---
17	ERW	1	0.13	53700	2948	53700	2948	----	---
18	ERW	12	74.89	53000	2909	48000	2635	2.33	9.3
19	ERW	2	13.31	53600	2942	52900	2904	0	1.4
20	ERW	1	17.50	52900	2904	52900	2904	----	---
21	ERW	12	163.80	52400	2876	47600	2612	0.62	9.2

TEST NOTES ON X-42 TENSILE SPECIMENS OF TABLE II

- Specimens 2,4, and 7 were loaded at constant load rate until failure. The average failure stress, $\sigma f1$, is 50500 psi. (2772 psi pressure).
- Specimens 1,5, and 8 were load cycled to increase the damage in the flaw region. The average failure stress,$\sigma f2$, is 48000 psi. (2635 psi pressure).
- Specimen 9 was not load cycled as Specimens 1,5, and 8 were and the failure stress, $\sigma f2$, was 48800 psi (2679 psi pressure) or 1.7% higher than the average $\sigma f2$ of Specimens 1,5, and 8.
- Specimen 3 was never subjected to a stress higher than the failure stress.
- Specimens 12,16,17,and 20 were loaded at constant load rate until failure. The average failure stress, $\sigma f1$, is 52800 psi. (2898 psi pressure).
- Specimen 19 was not cycled loaded. $\sigma f2$ was 52900 psi (2904 psi pressure) with a pressure reversal of 1.4%.
- Specimens 14 and 15 were cycle loaded to cause flaw damage. $\sigma f2$ average was 50300 psi (2761 psi pressure) and the pressure reversal was 5.3%.
- Specimens 18 and 21 were cycle loaded the most to cause flaw damage, $\sigma f2$ average was 47800 psi (2624 psi pressure) and the pressure reversal was 9.2%.

TABLE III: DATA SUMMARY FOR X-52 TENSILE SPECIMENS

Test No.	Mid-Cross Sec. Mtl.	No. of Load Cyc.	Total Test Time, Hrs.	Max. Stress Load psi	Equiv. Max. Pipe Press. psi	Failure Stress $\sigma f2$ psi	Equiv. Pipe Fail. Press. psi	Time With Fail Load, Hrs.	Pressure Reversal %
31	Plt	1	1.25	58136	3191	58136	3191	----	---
32	Plt	4	21.61	58337	3202	58337	3202	----	---
33	Plt	1	2.50	56737	3114	56737	3114	1.29	---
34	Plt	2	3.08	57978	3182	55684	3056	0.57	4.0
35	Plt	5	22.77	58427	3207	56626	3108	----	3.0
36	Plt	10	47.10	57945	3181	57459	3154	----	0.8
37	Plt	5	27.81	58191	3194	56102	3079	0.51	3.6
38	Plt	17	48.14	58446	3208	55922	3069	0	4.3
39	Plt	1	1.65	58140	3191	58140	3191	----	---
40	Plt	2	2.69	58311	3201	58102	3189	----	---
41	ERW	1	0.88	61884	3397	61884	3397	----	---
42	ERW	1	72.33	59516	3267	59516	3267	0.24	---
43	ERW	1	0.87	60989	3348	60789	3337	----	---
44	ERW	11	51.92	62026	3405	60144	3301	0.58	3.0
45	ERW	2	18.23	60557	3324	60557	3324	----	---
46	ERW	6+35	76.52	61241	3361	57009	3129	----	6.9
47	ERW	14	89.29	61682	3386	59674	3275	0.11	3.3
48	ERW	5+35	94.40	62483	3430	61334	3367	----	1.8
49	ERW	1	4.25	59548	3270	59584	3270	----	---
50	ERW	8+39	168.78	61986	3402	59477	3265	1.58	4.0

Numbers underlined indicate load cycles below the damage zone.

TEST NOTES ON X-52 TENSILE SPECIMENS OF TABLE III

- Specimens 31 and 39 were loaded at constant load rate until failure. The average failure stress, $\sigma f1$, is 58138 psi. (3191 psi pressure).
- Specimen 34 had one of the largest pressure reversals and it was not cycled, which indicates that it is difficult to lower $\sigma f2$ for this material.
- Specimens 34,37,and 38 all had essentially the same value for $\sigma f2$ and represented the largest pressure reversals. The minimum $\sigma f2$ (average) is 55903 psi (3068 psi pressure). Cycling seems to have little effect on $\sigma f2$.
- Specimens 41,43,and 49 were loaded with a constant load rate until failure. The average failure stress, $\sigma f1$, is 60752 psi (3335 psi pressure).
- Specimen 42 was loaded and held, load increased and held, etc. to get an estimate of the lowest failure load.
- Specimen 44 was cycled and the upper value of stress was higher than before. This indicates that strain hardening with several load cycles may be beneficial; however, Specimen 45 failed on the second load cycle and indicated the same failure stress as observed with Specimens 41 and 43 under constant load rate.
- Specimen 46 had some damage load cycles after the 35 cycles which were below the damage zone. This indicates the excessive cycles

(TEST NOTES ON X-52 TENSILE SPECIMENS OF TABLE III CONT.)

near the damage zone lever will change material properties in flaw zones and then significant flaw extension can occur. The flaw had extended through wall at failure.

- Specimen 47. The upper failure stress ($\sigma f1$) was raised by strain hardening; but, the lower failure stress ($\sigma f2$) was not changed with 13 load cycles in the damage zone. There was very little flaw extension but considerable necking.
- Specimen 48. The upper failure stress ($\sigma f1$) was raised with strain hardening. Many (35) cycles below the damage zone had no flaw extension. The flaw was being extended when the specimen failed.
- Specimen 50. Cycling stress 39 times to 55802 psi (3063 psi pressure) indicated no flaw damage when stress is below damage zone. The failure stress magnitude was achieved earlier in one test with no failure, indicating flaw damage occurs with stress in damage zone.

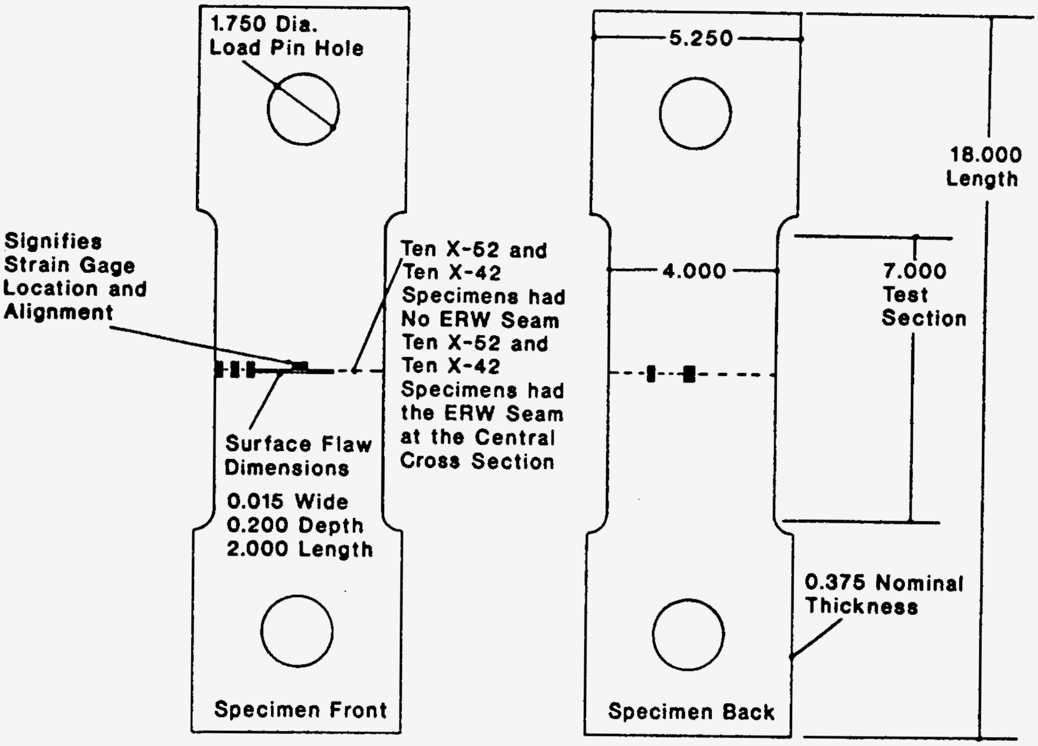

Fig.1 Tensile Specimen

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