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FATIGUE LIFE OF PIPELINES WITH DENTS AND GOUGES SUBJECTED TO CYCLIC INTERNAL PRESSURE

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ABSTRACT

Research has been conducted to study the effects of dents, gouges, and weld seams on pipelines under cyclic internal pressure loading. The work has involved pipes experimentally with D/t ratios from 18 to 94 and theoretically via finite element analysis with D/t ratios from 18 to 100.

According to both the experimental and theoretical work, plain smooth dents whose diameter is less than 5% of the pipe diameter should not be a problem, assuming that the cyclic pressure loading is not extreme. The experimental work indicated that gouge depth was an important factor in reducing the pipeline fatigue life; however, grinding was found to be a suitable form of repair for this defect. Categorizing gouges based on depth to wall thickness (d/t) was proven to be an effective means of classification. An analytical method was developed to predict the fatigue life of pipes subjected to cyclic internal pressure. The values are then compared to the experimentally obtained values.

EVALUATION OF EXISTING DATA

Review of existing data is important when attempting to identify and classify piping failures caused by mechanical damages. In spite of the extent of this information, there is still a void when considering guidelines for pipeline operators in assessing the consequences of dents and gouges on the fatigue life of pipes. A wealth of information has been obtained regarding dent classification (see resources cited in 2-6, 9-11, 15) as well as a survey form which was sent to forty-three oil and gas companies. Information regarding cyclic pressure variations (amplitude and frequency) for both oil and gas pipelines was also obtained from these resources. Figures 1 and 2 show the data obtained which show the typical cyclic pressure variations for an offshore transmission pipelines. Figure 1 shows the results for a gas transmission line, while Figure 2 provides data for an oil line where the high frequency data is considered typical every two days and the data for the latter three hours (4:00 - 7:00) is typical at all other times.

Shown in Figure 3 are the three types of dents which were classified as well as their respective cause of indentation. The important variables in determining fatigue life are listed in Table 1. As stated previously, this research should provide pipeline operators with guidelines which may be used to both determine the severity of existing defects and predict fatigue life assuming their presence in a piping system. The guidelines will be based on information obtained in the literature survey and specific findings associated with this research.

INTRODUCTION

One of the primary causes of leakage and failures in gas transmission pipelines has been mechanical damages such as dents, gouges, or a combination of both. In an effort to determine what work had been performed with respect to these damages, an extensive literature search was conducted (2-11). After review of this work, it was apparent that more research was needed. The initial phase of work involved the experimental and analytical study of plain dents; however, it was apparent at the completion of this work that continued studies were necessary in order to more fully understand the effects of dent in gouges. Although prior research indicated that dents with gouges in weld seams caused a reduction in cyclic pressure capacity, these sources failed to provide a means of classifying or quantifying the gouged type. As might be expected, a gouge which represents a scratch on the pipe surface can hardly be compared to one which is 90% of the wall thickness.

Although the study of the dents and gouges is of academic interest, the real issue is what effect do these damages have on pipelines and their operators. There are currently only very general rules which govern the range of allowable defects resulting from mechanical damages. One of the primary aims of this research is to provide understanding with regard to pipeline defects and determine which are most likely to cause failure. Guidelines will be developed for pipeline operators using the insights gained in this research based on several fundamental questions:

1. What dents, gouges, or combinations should be treated immediately?
2. Which mechanical defects are of no concern?
3. Where are the dents or gouges located relative to welds?
4. Which ones may be tolerated for a specific period of time at a possibly lower operating pressure?

The literature research indicated that there is an order of severity when considering defects in pipes. The work by Hopkins et al. (9) provides the following list,

1. Defects (gouges) in a dent
2. Dent in a weld seam
3. Plain dent, 4% (d/D)
4. Plain dent, 2% (d/D)
5. Plain defect

The primary objectives of this research were to:

1. Review past failures by studying historical data (11, 12-15) and published works (2-6, 9-11, 15) and use this information to categorically identify the different combinations of dents and gouges which exist.
2. Experimentally measure the fatigue lives of pipes which have been damaged with dents, gouges, or combinations of both.
3. Develop an analytical procedure for determining fatigue life assuming a specified defect is present in a pipe. This procedure will be based on finite element analysis with experimental verification.

EXPERIMENTAL METHODS

The experimental and theoretical work associated with this work involved several distinct phases. Initial work involved research on plain dents which only included finite element analysis as well as experimental fatigue testing of dented pipes subjected to cyclic internal pressure. Once this work was completed, it was apparent that work was required to specifically study the effects of dents with gouges and also this combination with weld seams. The work associated with the initial testing will be designated as *Phase I* (no gouges) with the latter work being *Phase II* (gouges).

Although results from the tests for *Phase I* and *II* will be reported, the focus of the information presented in this section will be on the latter work since *Phase I* work was presented previously in Reference 7. The results from *Phase I* indicated that neither dent type nor dent length were important when considering reduction in fatigue life, but the dent depth, pipe D/t ratio, and welding type were found to be important factors. In light of these discoveries, a test matrix was developed using dent depth ratios, *d/D*, of 5, 10, and 20% with the dent length to diameter ratio, *L/D*, being approximately 3.

Table 2 lists the specimens which were used in *Phase I* of the testing and those for *Phase II* are listed in Table 3. Included in both of these tables are the pipe wall thicknesses, material strengths, and maximum grade as specified by API Spec 5L. All test specimens were constructed from pipe sections and caps which were welded onto the pipe ends. The yield and ultimate strengths were obtained by cutting a section from each specimen and then sent to a materials testing laboratory.

Testing of each of the specimens involved three stages:

1. Gouging and/or denting of the pipes
2. Pressurizing to test pressure
3. Fatigue testing

The literature review and discussions with other researchers indicated that the defining characteristic which makes the dent/gouge combination so dangerous is the presence of microcracks at the base of the gouge. Research indicated that the most effective method of testing was to create a gouge first and then place a dent in the gouged region. Gouges in the pipe were installed in the pipe by a local machine shop. The most reproducible microcracks were made from a machined groove with an 0.002" radius.

Once the pipes were returned from the machine shop with the gouges installed, the dents were placed in the samples using the loading frame shown in Figure 4. In this denting procedure, the pipe specimen was placed in the testing apparatus where a steel saddle was used to brace the top portion of the pipe . A hydraulic cylinder was placed beneath the assembly to create the dents via a 24" X 24" X 2" steel plate.

The desired dent depths in the specimens for each of the samples at test pressure were 5, 10, and 20 % of the dent depth to pipe diameter ratio, d/D. In order to achieve these residual depths, the depths had to be over-estimated by approximately a factor of two since a portion of the dent would be removed with the disengagement of the hydraulic cylinder and the application of internal pressure. The actual applied dents were 10, 20, and 30% of d/D in order to obtain the desired depths specified previously. Diameter measurements were taken at the major and minor axes of the deformed pipe. Some of the gouges in the specimen were ground out prior to pressurization. This was accomplished using a hand-held grinder. After completion of the denting and grinding process, each sample was filled with water and pressurized to a specific test pressure with a simple water pump and the changes in diameter were measured.

The final stage of the experimental procedure involved testing with cyclic internal pressure. In order to use water as opposed to oil in the samples. an oil/water transfer cylinder was constructed so that a hydraulic pump could be used to pressurize the samples. This configuration is shown in Figure 5. A shut-down mechanism was installed so that the system would stop whenever the oil/water cylinder strokes were exceeded due to a fatigue failure in one of the specimens. Whenever a failure occurred in one of the samples, the failed region was removed and the adjacent regions were welded together. Table 4 presents the pressure ratios selected for fatigue testing of the specimens. The groupings and different pressures presented in this table were selected in order to minimize downtime and because of the existence of different pipe sizes, respectively.

EXPERIMENTAL RESULTS

The experimental results obtained for the fatigue specimens is presented in this section. Except for period stops due to failures, the cyclic testing was continuous. The presentation of the results will be divided relative to *Phase I* (no gouges) and *Phase II* (gouges) testing.

Tabulated results for the tests of *Phase I* is presented in Table 5. There are several significant findings when considering the results of these tests. After pressurization of the specimens, it can be seen from the table that the greatest dent removal occurred with the greatest initial indentations, which is especially true when considering the thinner-walled samples. This observation supports previous findings indicating that dents are typically removed from thin-walled specimens; however, dents in thick-walled specimens are more likely to remain unchanged. An example of this phenomena is seen in Specimen *C-2* which had an initial depth ratio of 20%, but after pressurization this value was reduced to 3.43%. Reference 7 has an in depth discussion of these results.

The work of *Phase II* (gouges) was developed to study dents with gouges and welds. Each pipe had a specific purpose in accomplishing this objective. The results of these tests are presented for each pipe in Tables 6 through 10. In presenting the specific findings for each pipe, a brief description of the purpose of each pipe will be made with the pertinent results. Pipes #2 and #3 were tested together as were Pipes #1, #4, and #5.

Pipe #2 was developed to study the effects of gouges with and without dents and the effects associated with the repair method of grinding the gouges out of the pipe. All applied imperfections were applied opposite the longitudinal weld. Pipe #3 was designed to study the effects of dents (without gouges) in conjunction with both longitudinal and girth welds. The most significant findings in Tables 6 and 7 concerning these two pipes are presented as follows:

Pipe #2 (Table 6)

- Gouge depth has a significant impact on the fatigue life of a pipe. It was found that a gouge depth of 5% (with no grinding) has a fatigue life which is three and a half times greater than a 15% gouge depth.

- Fatigue life was increased significantly when grinding was applied as a means of repair. The gouges which were ground had fatigue lives which were at least three times greater than non-ground counterparts. Also note that the cyclic pressure variation had a significant impact on fatigue life in that a pressure variation, ΔP, of 900 psi caused at least 10 times as much fatigue damage per cycle as a pressure cycle with $\Delta P = 400$ psi.

- The results indicate that the gouges without dents had the longest fatigue lives. This was to be expected since without the process of denting, no microcracks are achieved at the root of the gouge.

Pipe #3 (Table 7)

- The failures in the girth welds occurred before those placed along the longitudinal welds and 71° off the weld. The fatigue lives for the samples were 42,690 cycles as opposed to 61,218 and 78,754 cycles, respectively.

- Those dents which were placed 71° off of the longitudinal welds did not have significantly different fatigue lives than those placed directly on the longitudinal welds. Based on this and the previously cited findings, it would seem that girth welds have a greater impact when considering reduction in fatigue life than do longitudinal welds.

- This research indicates that plain dents have longer fatigue lives when not combined with gouges. This observation supports previous findings which demonstrated that gouges have the effect of seriously reducing the fatigue lives of pipes and dents.

Like Pipes #2 and #3, Pipes #1, #4, and #5 were designed to determine what effect gouges and welds have on the fatigue life of pipes with plain dents. The primary purpose of this group was to provide a greater range of pipe dimensions, D/t, for comparison. Dents and gouges (ground and non-ground) installed opposite the longitudinal weld seam were observed using Pipe #1 with a D/t ratio of 58, which was the largest D/t of all the gouge specimens. Like Pipe #3, Pipes #4 and #5 were used to study the effects of longitudinal and girth welds on dents. Pipes #1, #4, and #5 were first subjected to pressure variations of 500 psi and those dents or gouges which remained were tested at a ΔP of 1000 psi. The results of these tests are presented in Tables 8, 9, and 10 and a brief discussion on the specific findings associated with each pipe being presented below,

Pipe #1 (Table 8)

- The results for Pipe #1 support the results obtained for Pipe #1. Increased gouge depth causes a severe reduction in fatigue life as illustrated in that a pipe region with a 15% gouge had a fatigue of 3 cycles, whereas a 10% gouge had a fatigue life of 10%.

- Like previous conclusions, the process of grinding out the gouges was found to increase fatigue life significantly. Table 8 indicates that gouge numbers 7 through 10, which had been ground, had longer fatigue lives than their non-ground counter parts in regions 1 through 4.

- As illustrated previously, the gouges with no dents had the longest fatigue lives and the process of grinding does not appear to significantly increase the fatigue lives of gouges which do not have dents.

Pipes #4 and #5 (Tables 9 and 10)

- The differences in Pipes #4 and #5 are primarily dimensional in that #4 had a D/t ratio of 25 and #5 a D/t of 46. Both pipes indicate that the increased dent depth causes a reduction in fatigue life. Although the 15% dents in Pipe #4 did fail, it is important to note that this did not occur until 90,000 cycles. This re-emphasizes the important role that gouges have in reducing the fatigue life of plain dents.

- The fatigue lives for the dents in Pipe #5 are somewhat lower than the respective dents installed in Pipe #4. This indicates that although dent depth does play an important role in reducing fatigue life, the D/t ratio of the pipe also plays a part. Perhaps this is to be expected when considering the higher hoop strains which exist in the pipe with the thinner wall. These results suggest that the fatigue lives in two different pipes having exact dent depths can be expected to be lower in the pipe which possesses the largest D/t ratio.

FINITE ELEMENT AND FATIGUE ANALYSIS

Understanding the fatigue mechanism and guidance for cases which were not examined experimentally can be accomplished using finite element analysis. The objectives of this process were to determine which variables were most important in determining the fatigue life of a dented pipe and to develop a procedure for determining fatigue life of pipes with plain dents using stress intensification factors ($\Delta\sigma/\Delta P$) based on the finite element work. For a more rigorous discussion in the finite element methodology, refer to the work by Fowler et al. (7).

Elastic-plastic analysis (as opposed to purely elastic) was found to be the most useful means for determining accurate $\Delta\sigma/\Delta P$ values and for modeling the dent removal phenomena using finite elements. Analysis was performed in pipes which had comparable D/t ratios and material properties as those used experimentally. The models were built to determine a range of important fatigue parameters, which as indicated by the test results were D/t, d/D, σ_y, and P. The models were created using half-symmetry and three-dimensional shell elements with rigid surfaces used to model the indenter plate. Like the experimental work, the models were loaded in three distinct steps - denting, releasing the dent, and pressure cycling. As was the case with the actual pipes, there was difficulty in achieving significant residual dent depths, especially when considering the thinner-walled pipes. In the analysis it was very difficult to obtain a residual dent greater than 1%, regardless of the initial indentation, for a pipe with a D/t ratio of 50 and constructed using X42 material. Much like the experimental work, cyclic internal pressure was applied the pipes at specific mean pressures and differentials.

Figure 6 provides a diagram illustrating the stress variation on the inside and outside surfaces of the dented pipe based on the finite element analysis. Note that tension stresses where cracking may start occur on the outside of the pipe where the dent is made and on the inside of the pipe at about 80° from the indenter. From this type of information, a series of $\Delta\sigma/\Delta P$ values were obtained for the range of pipes considered. Figure 7 provides a graphical representation of these values as a function of D/t ratios for a specific mean pressure and material yield strength. This information can be used to predict the fatigue lives of samples which were not tested experimentally.

After completion of the finite element work, the final step in the theoretical framework was the fatigue life prediction for dented pipes subjected to cyclic internal pressure loading. The conventional Miner's Rule (Refernec 16) for fatigue analysis with a power law idealization of the fatigue curve for stress range as a function of cyclic life was deemed appropriate. The S-N curve first used for this procedure was the API-RP2A curve X' (Reference 1); however, the DOE-B curve was found to give results which were more accurate when compared to the experimental results. This equation is described mathematically using the following equation,

$$N = 4.424X10^{23}\left(\left[\frac{\Delta\sigma}{\Delta P}\right]\cdot\Delta P\right)^{-4} \tag{1}$$

An example problem is provided so that the reader may apply these developments practically. Assume that a pipe with a D/t ratio of 50 has a dent depth ratio, d/D, of 5% and is subjected to pressure fluctuations of 500 psi. The fatigue life is calculated using the DOE-B curve as follows,

$$\left[\frac{\Delta\ \sigma}{\Delta\ P}\right] = 106 \qquad \textit{(See Figure } \cancel{8}\textit{)}\ 1 \tag{2}$$

$$N = 4.424X10^{23}\ (106\cdot 500\ psi)^{-4} = 56{,}068\ cycles \tag{3}$$

Computation of the above calculation assuming the API X' curve leads to unrealistically conservative answers (6,384 cycles) when compared to the experimentally obtained results (sample *C*-2, 118,055 equivalent cycles). Thus, the fatigue life for a pipe which has been damaged with a plain dent can be estimated most accurately using the DOE-B curve, but until this work no procedure has been developed to incorporate factors that account for the presence of gouges and welds in dents. Using the finite element stress intensification factors and experimental results, a procedure was developed to meet this objective by creating gouge/weld correction factors. The following list outlines the steps which would be required for an operator to calculate the fatigue life of a damaged pipe using the DOE-B curve and the gouge correction factors. Usually it will not be possible to obtain the original dent depth, so the values presented are based on the final residual dent depths. For the purpose of presenting an example problem, a sample gouge correction factor listing has been provided in Tables 11 and 12.

1. Determine the dent depth, d/D, and gouge depths, d/t, with the line depressurized.
2. Using the mean operating temperature, P_{mean}, D/t, and d/D values, determine the stress intensification factor, $\Delta\sigma/\Delta P$, from the existing tables.
3. Calculate the <u>nominal</u> fatigue life for the pipe using the DOE-B curve (using Equation 1)
4. Determine the gouge/weld correction factor from the existing tables using the parameters defined in Step #1.
5. Calculate the corrected fatigue value by multiplying the nominal fatigue life (Step #3) by the gouge/weld correction factor (Step #4).
6. The fatigue life minus the number of cycles already experienced by the pipe provides the remaining life for the sample.

For purpose of example, assume a 12 inch nominal pipe with a 0.364" wall which has a residual dent that is 6% of its diameter and away from the longitudinal weld seam. A gouge of 10% of the wall is present and has been ground out. The D/t of the pipe is 35 with a material yield of 52,000 psi. The pipe is subjected to a pressure variation ΔP of 400 psi at a mean pressure, P_{mean}, of 500 psi. Based on these given conditions, what is the expected life of the pipe?

The prediction of the <u>nominal</u> fatigue life for the pipe is based upon the DOE-B curve using the $\Delta\sigma/\Delta P$ value provided in Figure 8 ($\Delta\sigma/\Delta P = 88$),

$$N = 4.424X10^{23}\ (88\cdot 400\ psi)^{-4} = 421{,}905\ cycles \tag{4}$$

From Tables 11 and 12 it can be seen that the fatigue life of the gouged sample will be reduced from approximately 3 to 20% of the life for an unground dent. A conservative approach provides the minimum life,

$$N = 421{,}906 \cdot (.03) = 12{,}657 \ cycles \tag{5}$$

CONCLUSIONS AND RECOMMENDATIONS

1.0 This research has provided a method for estimating the fatigue life of a pipe by incorporating mean operating pressure, cyclic pressure variations, and dimensional parameters such as D/t, d/D, d/t, as well as the importance of the weld location. Although this methodology and the results provided herein are encouraging, continued research could be valuable for the purpose of determining the intermediate pipe dimensions which exist between the extreme D/t ratios considered for this project. It seems quite possible that a complete tabulated system could be developed which would include a wide range of pipe sizes and defects.

2.0 Plain dents act as a stress concentration factor (SCF) for cyclic pressure. For small D/t pipe, this SCF can be as high as 5. For lower D/t pipe, a maximum SCF of 3 or less results because of cyclic plasticity and shape changes of the dents. The SCF is very heavily dependent on the dent depths, but not as dependent on the dent shape. The maximum SCF's occur with the largest dents.

3.0 Fatigue analysis with conventional fatigue analysis procedures for dents without gouges under cyclic pressure is mostly satisfactory and conservative. Operators should get good results using this methodology.

4.0 Gouges combined with dents can be very dangerous under cyclic pressure loading. Gouges are dangerous because of microcracks which form as a dent/gouge is made. This microcracks eliminate a large portion of the fatigue crack growth process and are the reason that the fatigue life is low. Limited testing teaches that gouges whose depth is 15% or more of the wall thickness may fail immediately. Gouges whose depth is 5-10% of the wall thickness may fail after a few thousand cycles, which can represent less than 1% of what the life of the dent would be without gouges. Tables 12 and 13 present life factors to account for gouges using the plain dent calculations.

5.0 Grinding out gouges until there are no indications with dye penetrant or magnetic particle examination can greatly extend the life of the dent by a factor of 10 or more. However, it is unlikely that grinding will achieve the cyclic pressure capacity of the ungouged pipe.

6.0 Further work should be concentrated in collecting more test data and in examination of the basic gouge making characteristics of common construction equipment such as backhoes and trenchers. More test data could be used to develop statistics (mean and standard deviation) of gouge lives so that a meaningful reliability analysis could be done.

NOMENCLATURE

d	Dent depth (inches)
D	Pipe outside diameter (inches)
L	Dent length (inches)
t	Pipe wall thickness (inches)
P	Internal pressure (psi)
ΔP	Cyclic pressure range (psi)
$\Delta\sigma$	Hoop stress variation due to cyclic pressure (psi)
σ_{yield}	Yield strength of pipe (psi)
N	Number of cycles

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TABLE 1
RANGE OF DIMENSIONAL AND NON-DIMENSIONAL VARIABLES

Dimensional and Non-Dimensional Variables	Range of Data to be Considered
Dent Shape	*a*, *b*, or *c* (see Figure 3)
D_o/t	*Test I* - 18-94
d/D	1% - 20%
L/D	2 - 5
Pressure Fluctuations	Gas: 700-1000 psi Oil: 550-1200 psi
$\Delta\sigma/\Delta P$	To be determined by Analysis
Process of Manufacture	SMLS, ERW, DSAW
Surface Condition	Smooth, Rough, Gouge, Weld

TABLE 2
MECHANICAL PROPERTIES AND DIMENSIONS OF SPECIMENS USED IN *PHASE I* PLAIN DENTS

Specimen Number	D	t	D/t	Hoop Yield Stress (ksi)	Hoop Ultimate Strength (ksi)	Elongation (%)	Maximum Grade	Comment
A-1	12.741	.685	18.6	55.1	72.4	39	X52	Seamless
A-2	12.73	.670	19.0	65.8	88.9	32	X60	Seamless
B-1	12.761	.312	40.9	53.1	82.0	32	X52	Seamless
B-2	12.75	.25	51.0	57.3	74.4	33	X52	ERW
H	12.751	.515	24.76	52.1	74.0	37	X52	Seamless
E	12.72	.40	31.8	51.2	74.7	32	X46	Seamless
F	12.72	.40	31.8	51.2	74.7	32	X46	Seamless
G	12.726	.253	50.3	84.0	92.2	20	X80	Seamless
I	12.75	0.255	64.4	52.4	72.7	38	X52	ERW
J	24	0.198	94.1	78.6	92.6	32	X70	ERW

TABLE 3
MECHANICAL PROPERTIES AND DIMENSIONS OF SPECIMENS USED IN *PHASE II* PIPES WITH DENTS AND GOUGES

Pipe Specimen #	D	t	D/t	Hoop Yield Stress (psi)	Hoop Ultimate Strength (psi)	Elongation (%)	Maximum Grade	Comment
1	12.75	0.220	58	66,300	74,800	23.35	X56	ERW
2	12.75	0.399	32	78,200	87,000	33.0	X70	ERW
3	12.75	0.398	32	75,700	83,000	31.0	X70	ERW
4	12.88	0.512	25	47,200	73,700	41.0	X42	ERW
5	12.75	0.278	46	76,800	87,400	28.0	X70	ERW

TABLE 4
PRESSURE RANGES FOR SPECIMENS USED IN *PHASE I* AND *PHASE II*

Sample Designation		Pressure Range for 1st 50,000 Cycles (psi)	Pressure Range for 2nd 50,000 Cycles (psi)
Phase I	Samples A - H	100 - 550	100 - 1200
	Samples I & J	100 - 400	100 - 900
Phase II	Samples #2 & #3	500 - 900	100 - 1200
	Samples #1, #4, & #5	500 - 1000	50 - 1050

TABLE 5
SUMMARY OF EXPERIMENTAL DATA FOR *PHASE I* PLAIN DENTS, D/t=18-51

Specimen	σ_y (ksi)	σ_u (ksi)	$(d/D)_i^{\text{Note 1}}$ %	$(d/D)_f^{\text{Note 2}}$ %	1st Series (ΔP=650 psi) # Cycles	2nd Series (ΔP=1200 psi) # Cycles	Failure
A-1	55.1	72.4	5.0	3.92	23,875	76,125	N
	55.1	72.4	10.0	7.84	23,875	76,125	N
	55.1	72.4	15.0	10.01	23,875	76,125	N
A-2	65.8	88.9	5.0	3.92	23,875	76,125	N
	65.8	88.9	10.0	7.84	23,875	76,125	N
	65.8	88.9	15.0	10.01	23,875	76,125	N
B-1	53.1	82.0	5.0	2.21	23,875	6,067	Y
	53.1	82.0	10.0	3.92	23,875	2,611	Y
	53.1	82.0	20.0	3.92	8,200	0	Y
C-2	74.4	74.4	5.0	1.96	23,875	11,267	Y
	74.4	74.4	10.0	2.43	23,875	3,950	Y
	74.4	74.4	20.0	3.43	23,875	1,503	Y
					1st Series (ΔP=650 psi) # Cycles	2nd Series (ΔP=1100 psi) # Cycles	
H	52.1	74.0	4.80	4.11	51,400	62,338	N
	52.1	74.0	9.39	5.92	51,400	63,228	N
	52.1	74.0	18.30	11.33	51,400	11,333	Y
E	51.2	74.7	7.54	4.77	51,400	62,338	N
	51.2	74.7	8.24	4.83	51,400	62,338	Y
	51.2	74.7	17.07	7.42	51,400	14,232	Y
F	51.2	74.7	5.19	3.73	51,400	62,338	N
	51.2	74.7	9.21	5.24	51,400	18,526	Y
	51.2	74.7	17.24	7.18	51,400	6,544	Y
G	84.0	92.2	6.78	1.57	51,400	62,338	N
	84.0	92.2	12.68	4.77	51,400	1,582	Y
	84.0	92.2	17.23	5.92	42,739	0	Y

Notes:
1. Dent depth ratio prior to pressurization
2. Dent depth ratio after pressurization

TABLE 6
SUMMARY OF EXPERIMENTAL DATA FOR *PHASE 1* PLAIN DENTS, D/t=64-94

Specimen	Dent #	σ_y (ksi)	σ_u (ksi)	$(d/D)_i$ %	$(d/D)_r$ %	1st Series (100-400 psi) # Cycles	2nd Series (100-900 psi) # Cycles	Failure
I-1[1]	1	52.4	72.7	5.0	3.48	52,354	44,651	N
I-2	2	52.4	72.7	15.2	7.82	52,354	33,132	Y
I-3	3	52.4	72.7	10.4	6.28	52,354	16,117	Y
I-4 *	4	52.4	72.7	10.3	6.16	52,354	9,480	Y
I-5	5	52.4	72.7	9.2	5.91	52,354	—	
I-6	6	52.4	72.7	5.4	4.59	52,354	44,651	Y
I-7	7	52.4	72.7	11.8	6.95	52,354	32,584	Y
I-8	8	52.4	72.7	4.3	3.97	52,354	44,651	N
J-1[2]	1	78.6	92.6	5.5	3.52	52,354	44,651	N
J-2	2	78.6	92.6	5.7	5.35	52,354	44,651	N
J-3	3	78.6	92.6	10.0	6.22	52,354	44,651	N
J-4 *	4	78.6	92.6	10.8	5.89	8,709	—	Y
J-5	5	78.6	92.6	12.3	6.28	37,302	—	Y
J-6	6	78.6	92.6	6.3	5.07	20,306	—	Y

Notes:

1) The *I-n* specimens utilize the 12 inch nominal pipe with a wall thickness of 0.198 inches. The respective D/t ratio for this pipe is 64.
2) The *J-n* specimens utilize the 24 inch nominal pipe with a wall thickness of 0.255 inches. The respective D/t ratio for this pipe is 94.
3) The location of failure is coded by using Figure 4.1.
4) Equivalent number of cycles acquired by using API X' curve.

* - Indicates that failure occurred in longitudinal weld seam.

TABLE 7
SUMMARY OF EXPERIMENTAL DATA FOR PIPE #2, D/t=32

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	% Gouge Depth (d/t)	Gouge Ground Smooth	Cycles @ $\Delta P=400$ psi	Cycles @ $\Delta P=900$ psi	Failure (YES/NO)	Location of Failure
1	10	7.06	15	NO	6,441	—	YES	Midpoint
2	10	7.21	10	NO	9,046	—	YES	Burst
3	10	7.17	5	NO	23,548	—	YES	Midpoint
4	—	—	10	NO	49,331	29,423	NO	—
5	—	—	10	YES	49,331	29,423	NO	—
6	10	*	5	YES	49,331	5,420	YES	Midpoint/ Transition Area
7	10	*	10	YES	31,948	—	YES	Transition Area
8	10	*	15	YES	43,097	—	YES	Midpoint

* - Indicates that $(d/D)_f$ results not available

TABLE 8
SUMMARY OF EXPERIMENTAL DATA FOR PIPE #3, D/t=32

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	Dent location relative to welds	Cycles @ $\Delta P=400$ psi	Cycles @ $\Delta P=900$ psi	Failure (YES/NO)	Location of Failure
1	15	9.93	On longitudinal	49,331	—	YES	Midpoint
2	10	8.08	On longitudinal	49,331	11,887	YES	Midpoint
3	5	5.16	On longitudinal	49,331	29,423	NO	—
4	10	7.11	On girth weld, +90° off long. weld seam	49,331	2,824	YES	Midpoint
5	10	6.66	On girth weld, 90° off long. weld seam	42,690	—	YES	Midpoint
6	5	5.40	71° off long. weld seam	49,331	29,423	NO	—
7	10	7.94	71° off long. weld seam	49,331	29,423	YES	Transition area
8	15	9.75	71° off long. weld seam	45,221	—	YES	Transition area

TABLE 9
SUMMARY OF EXPERIMENTAL DATA FOR PIPE #1, D/t=58

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	% Gouge Depth (d/t)	Gouge Ground Smooth	Cycles @ ΔP=500 psi	Cycles @ ΔP=1000 psi	Failure (YES/NO)	Location of Failure
1	10	4.88	15	NO	3	—	YES	Burst on gouge
2	10	4.77	10	NO	4,408	—	YES	Burst on gouge
3	10	4.69	5	NO	10,111	—	YES	Burst on gouge
4	10	4.50	5	NO	7,092	—	YES	Burst on gouge
5	—	—	10	NO	54,894	29,808	NO	—
6	—	—	10	NO	54,894	29,808	NO	—
7	10	4.76	5	YES	54,894	29,808	YES	Transition area
8	10	4.69	5	YES	54,894	4,306	YES	Transition area
9	10	4.78	10	YES	34,000	—	YES	Pinhole leak (not in gouge)
10	10	5.49	15	YES	15,309	—	YES	Transition area

TABLE 10
SUMMARY OF EXPERIMENTAL DATA FOR PIPE #4, D/t=25

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	Dent location relative to welds	Cycles @ ΔP=500 psi	Cycles @ ΔP=1000 psi	Failure (YES/NO)	Location of Failure
1	15	9.88	69° off longitudinal	52,188	36,992	YES	Midpoint of dent
2	10	9.74	69° off longitudinal	52,188	36,992	NO	—
3	5	4.41	69° off longitudinal	52,188	36,992	NO	—
4	15	11.2	69° off longitudinal	52,188	9,652	YES	Transition area

TABLE 11
SUMMARY OF EXPERIMENTAL DATA FOR PIPE #4, D/t=46

Dent/Gouge #	% Dent Depth (d/15$_i$	% Dent Depth $(d/D)_f$	Dent location relative to welds	Cycles @ ΔP=500 psi	Cycles @ ΔP=1000 psi	Failure (YES/NO)	Location of Failure
1	5	6.17	79° off longitudinal	64,144	8,582	YES	Transition Area (Weld Seam)
2	10	4.26	79° off longitudinal	64,144	19,205	YES	Transition Area
3	5	6.78	90° off longitudinal (on girth weld)	25,013	—	YES	Midpoint (Girth Weld)
4	15	3.76	79° off longitudinal	64,144	19,205	NO	—
5		6.72	79° off longitudinal	32,875	—	YES	Midpoint (Weld Seam)

TABLE 12
THEORETICAL GOUGE CORRECTION SUMMARY OF FACTORS FOR PIPE #1, D/t=58

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	% Gouge Depth (d/t)	Gouge Ground Smooth	Cycles $@\Delta P=500$	Cycles $@\Delta P=1000$	Failure (YES/NO)	Gouge Theoretical Correction
1	10	4.88	15	NO	3	—	YES	0.000
2	10	4.77	10	NO	4,408	—	YES	0.0051
3	10	4.69	5	NO	10,111	—	YES	0.0116
4	10	4.50	5	NO	7,092	—	YES	0.0082
5	—	—	10	NO	54,894	29,808	NO	0.173**
6	—	—	10	NO	54,894	29,808	NO	0.173**
7	10	4.76	5	YES	54,894	29,808	YES	0.173
8	10	4.69	5	YES	54,894	4,306	YES	0.080
9	10	4.78	10	YES	34,000	—	YES	0.0392
10	10	5.49	15	YES	15,309	—	YES	0.0177

** - Indicates that no failure occurred and that this Usage Factor could be higher

TABLE 13
THEORETICAL GOUGE CORRECTION SUMMARY OF FACTORS FOR PIPE #2, D/t=58

Dent/Gouge #	% Dent Depth $(d/D)_i$	% Dent Depth $(d/D)_f$	% Gouge Depth (d/t)	Gouge Ground Smooth	Cycles $@\Delta P=500$	Cycles $@\Delta P=900$	Failure (YES/NO)	Gouge Theoretical Correction
1	10	7.06	15	NO	6,441	—	YES	0.0318
2	10	7.21	10	NO	9,046	—	YES	0.045
3	10	7.17	5	NO	23,548	—	YES	0.116
4	—	—	10	NO	49,331	29,423	NO	1.21**
5	—	—	10	YES	49,331	29,423	NO	1.21**
6	10	*	5	YES	49,331	5,420	YES	0.80
7	10	*	10	YES	31,948	—	YES	0.158
8	10	*	15	YES	43,097	—	YES	0213

* - Indicates $(d/D)_f$ results not available

** - Indicates that no failure occurred and that this Usage Factor could be higher

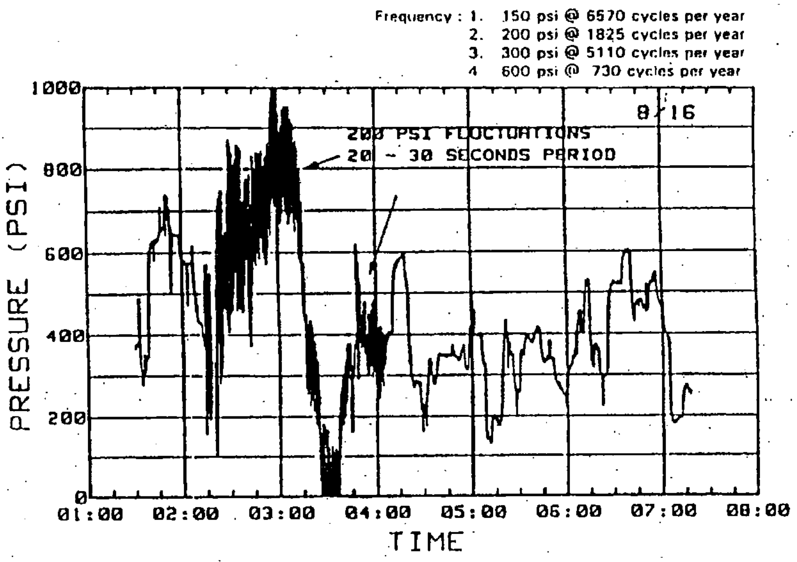

FIGURE 1
OPERATING PRESSURE FLUCTUATIONS TYPICAL TO OIL PIPELINES

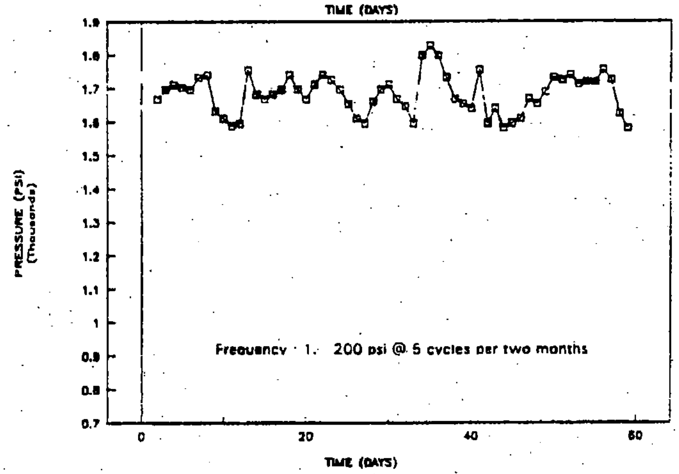

FIGURE 2
OPERATING PRESSURE FLUCTUATIONS TYPICAL TO GAS PIPELINES

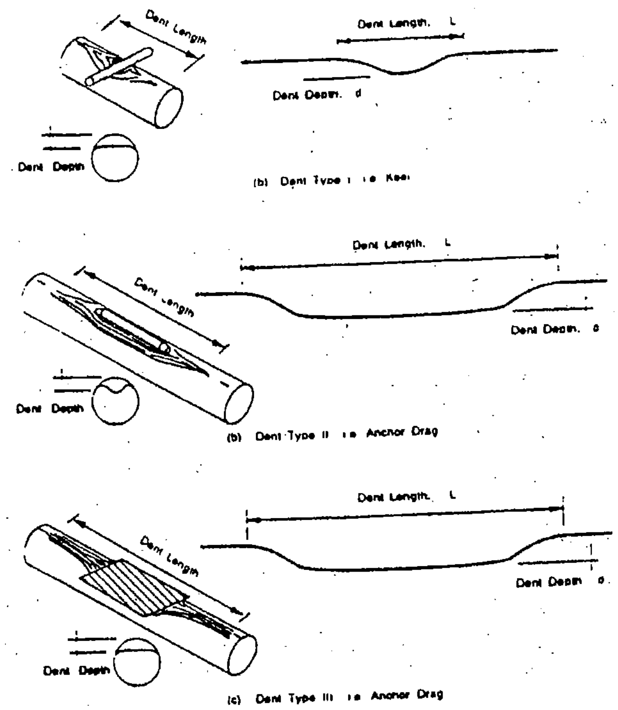

FIGURE 3
DENT TYPES

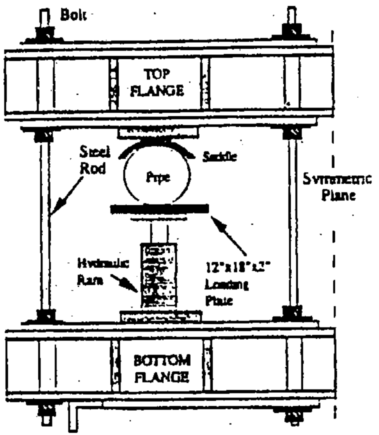

FIGURE 4
LOADING FRAME

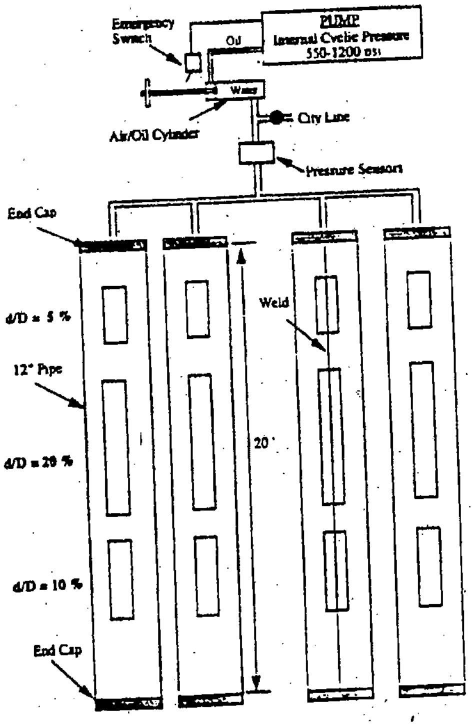

FIGURE 5
TEST SET-UP

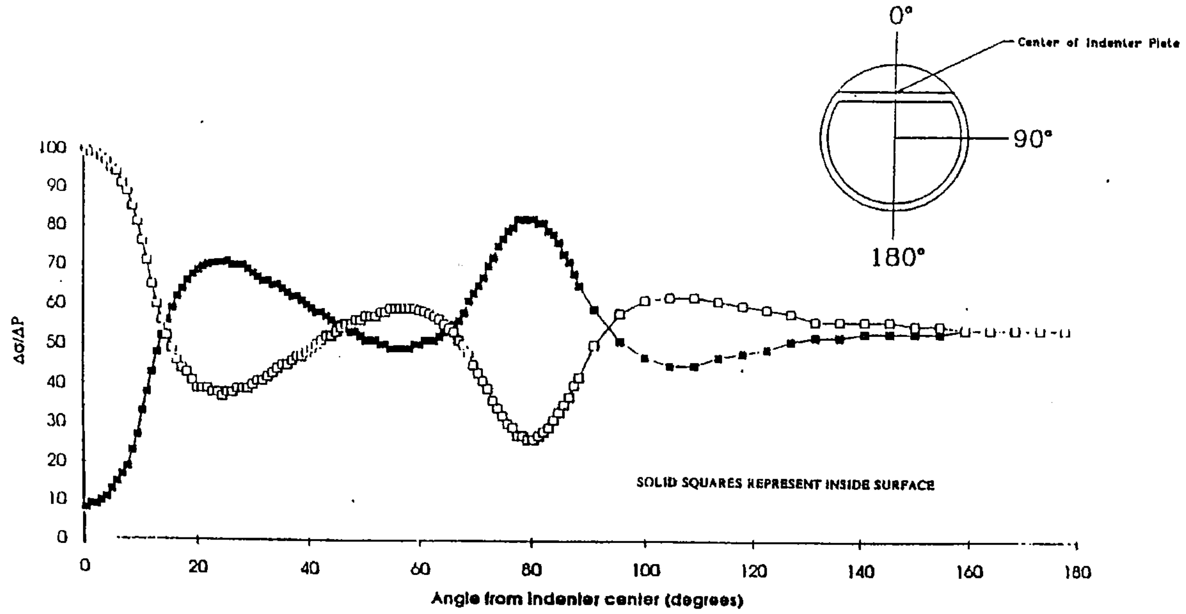

FIGURE 6
STRESS VARIATION ON INSIDE AND OUTSIDE SURFACE OF MODEL AT 500 psi WITH D/t=110, d/D=5%, AND SMYS=70,000 psi

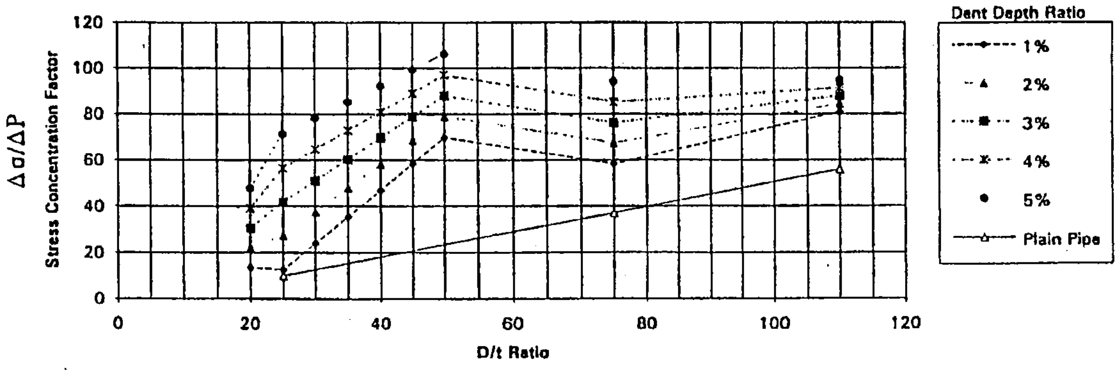

FIGURE 7
STRESS CONCENTRATION FACTOR AS A FUNCTION OF D/t RATIO AND DENT DEPTH FOR A MEAN PRESSURE OF 500 psi AND PIPING WITH 52,000 psi YIELD STRENGTH