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Fatigue Behavior of Dented Petroleum Pipelines—Task 4

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16. Abstract

Dents is pipelines can seriously reduce their design lives. Dents cause the development of stress concentrations which make dents susceptible to fatigue failures. Acceptance criteria of dents is currently based on dent depth alone. To understand the behavior of dents in pipelines, a research program involving both experimental testing and finite element analysis was conducted. Fifteen pipe specimens ranging in diameters from 12 in. to 36 in. with wall thickness of either 1/4 in. or 3/8 in. Various types of damage were studied, including dents due to rocks, dents formed with backhoe teeth, and short longitudinal dents with simulated damage. The effect of dent restraint was also investigated. Two types of fatigue failures were observed: cracks developing from machined gouges in the dent troughs and periphery cracks at plain (without machined gouges) dents. Three dimensional shell element finite element models were given elasto-plastic behavior for modeling dents in pipelines. Parameters modeled include dent depth, dent type, dent restraint, pipe diameter, thickness, grade, longitudinal stress, pipe support, and pressure at indentation. For the given parameters, the rebound behavior and stress behavior of dents was investigated. The displacement data was studied to understand the rebound characteristics of dents. From the finite element modeling, the rebound characteristics can be predicted for a broad range of values for the various parameters.

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Fatigue Behavior of Dented Petroleum Pipelines

Final Report

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Office of Pipeline Safety
U.S. Department of Transportation

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The fatigue test program and its results reported are the results of a research project sponsored by the Office of Pipeline Safety, U.S. Department **of** Transportation (Solicitation No. DTRS56-95-R-0003) The research was performed by the Texas Transportation Institute, Texas A&M University System in College Station, Texas. The research project was coordinated for the Office of Pipeline Safety by William Gute; Gopala (Krishna) Vinjamuri, Materials Engineer, provided technical direction **as** the Contracting Officer's Technical Representative.

SUMMARY

The fatigue behavior of damaged on-shore petroleum pipelines was investigated both experimentally and analytically. Various types of damage were studied, including dents due to rocks, dents formed with backhoe teeth, and short longitudinal dents with simulated gouges. A dent causes a localized concentration of the pipe wall stresses that result from internal pressures. Fluctuation of the pressure can result in fatigue crack initiation and propagation. The effect of dent restraint was also investigated.

A total of fifteen specimens were fatigue tested. These specimens had a range of nominal outside diameters from 12 in. to 36 in. with wall thickness of either 1/4 in. or 3/8 in. This resulted in a range of diameter-to-thickness ratios from 34 to 96. The number of dents per specimen varied from 10 for the smaller diameter pipes to 3 for the larger diameter pipes. Dent depths ranged from 5 to 18.75 percent of the pipe diameter. Each specimen was subjected to a hydraulically varied pressure distribution to simulate actual pipeline pressure conditions. Each specimen was pressure-cycled until all the dents in the specimen failed or 100,000 cycles had accumulated. Failed dents, as defined by leakage, were either repaired or removed from the specimen by sectioning.

Three types of dents classified as type A, BH, and R were tested. Type A consists of a four-inch longitudinal dent. Type BH consists of longitudinal and transverse dents caused by a backhoe tooth. Type R consists of rocks. Type A and BH dents were tested with and without restraint. Type R dents were tested with restraint. Mechanical damage including machined gouges and scratches were tested with all type A dents.

The dent rebound behavior was studied for the unrestrained dents. Dent rebound increases with an increase in the diameter-to-thickness ratio. Type A dents experienced more rebound than Type BH dents. The rebound of Type A dents allowed the center of the dent to bulge to put the area in reverse curvature. This behavior is related to the length of the dent. Type BH dents did not have the behavior of Type A dents due to the short dent length and sharp dent

geometry. The dent Type A rebound after pressurization of dents with different depths yielded similar final depths which makes it impossible to know the extent of damage if only the final dent depth is known.

Three types of fatigue failures were observed experimentally: cracks developing in the troughs of Type A unrestrained dents, periphery cracks in all dent types, and internal cracks in the trough of restrained rocks. As expected, dents with deeper initial dent depths exhibited shorter fatigue lives than shallower dents. However, due to the rebound after denting and during pressurization, it is difficult to determine the initial dent depth. The unrestrained Type A dents had relatively low fatigue lives due to the dent rebound behavior in addition to the mechanical damage. The fatigue lives of dents with periphery cracks is longer. Restraint of Type A dents did not allow the rebound, causing peripheral cracking instead of cracking in the dent trough. Failures of Type A dents occurred at all dent depth-to-diameter ratios tested. Failures of Type BH only occurred for dent depth-to-diameter ratios of ten and above. The failures from internal cracks under rocks had similar fatigue lives as Type BH failures. Only a few of these crack types developed.

A finite element parametric study was performed to understaud the behavior of dents in pipelines. Three dimensional shell element models were given elasto-plastic behavior for modeling dents in pipelines. Various dent and pipe parameters were modeled. The dent parameters include dent depth, dent type, and dent restraint. Dent type includes geometry considerations such as dent length and dent orientation. Pipe parameters include diameter, thickness, grade, longitudinal stress, pipe support, and pressure at indentation. For the given parameters, the rebound behavior and stress behavior of dents was investigated. The displacement data was studied to understand the rebound characteristics of dents. Stress data was studied to determine failure modes of different combinations of dents and pipes.

Restrained dents were modeled to understand the failure modes found in the experimental program. Spherical restrained dents were used to simulate dents caused by rocks. Restrained longitudinal dents were also modeled.

Models were compared with data from the experimental program to verify the results of the models. Rebound data and failure modes were compared between models and experimentally tested dents.

Chapter One
INTRODUCTION

1.1 PROBLEM STATEMENT

Pipeline failures are often associated with fatigue crack development. Fluctuation in pressure fiom pumping, scheduled pressure testing, pressure surges, and product density changes causes stress cycles to accumulate over the life of pipes. In the design and evaluation of pipelines for fatigue, both the longitudinal seam and the full penetration groove weld used to joint pipe sections are critical. Current fatigue design provisions, coupled with competent construction and inspection, yield satisfactory performance over the intended service life of the pipeline. However, accidental damage to the pipe can result in a defect, such as a gouge or dent, with a stress condition more severe than the designed welds. Gouges, nicks, or scratches typically result in initial flaws that are larger than those tolerated in the pipeline weldments. Stress concentrations caused by dents increase the range of the stress cycles. The increase in flaw sizes and stress concentrations accelerate the growth of fatigue cracks which can lead to leakage rupture of pipelines.

Two types of pipeline dents are typically categorized: excavation dents and settlement-induced dents. Excavation dents occur fiom contact with earth-moving equipment (backhoe bucket teeth, for example) during construction or Service of the pipeline. The excavation dents are usually accompanied by gouges or damage that contain initiation sites for fatigue crack development. These dents are most often found in the upper half of the pipe due to the location and direction of excavation. Settlement-induced or rock dents occur when a pipeline is inadvertently laid on or settles onto an unyielding rock. The weight of the pipe, the soil overburden, hydrostatic test water, or product can cause the pipe to deform around the rock. Unlike excavation dents, settlement-induced dents are unable to rebound with pressurization, thus changing its fatigue behavior when compared to unrestrained excavation dents. Settlement-induced dents are found on the bottom half of the pipe.

Acceptability of dents in pipelines is currently based on the dent depth-to-diameter ratio (*d/D*) at the time of detection without regard to diameter, thickness, or any aspect of the dent geometry. This method does not account for differences in dent shape or pipe variables. Acceptance based strictly on dent depth may lead to overly restrictive estimates of damage so as to include the entire spectrum of different dent types for all pipe sizes. This, in turn, may result in unnecessary repair of damaged pipelines that may otherwise have satisfactory performance. Conversely, certain combinations of dent types and pipe sizes may result in fatigue failure from dents acceptable under the current criteria. Without a clear understanding of the denting. mechanism and what types of dents can form under various load conditions, a single measure of dent depth may not always provide information to estimate dent criticality with a reasonable degree of certainty. No knowledge of the dent history (initial dent depth, rebound characteristics, etc.), which influences dent fatigue behavior, may lead to unreliable acceptance or rejection of dents. Thus, an improvement in the acceptance criteria can improve the operational reliability of the pipeline, as well as reducing costs by providing a rational method of dent evaluation. This will require an understanding of the possible failure modes for various combinations of dent shapes and pipe sizes.

1.2 CURRENT ACCEPTANCE CRITERIA

The design, fabrication, and operation of pipelines for the transportation or transmission of both liquid and gas petroleum product is governed by the pressure piping codes issued by the American Society of Mechanical Engineers **(ASME).** Separate codes are provided for both liquid and gas petroleum pipelines. Gas pipelines typically operate at higher pressures than liquid pipelines. Due to the compressibility of gas, the possibility of an explosive rupture is much greater than in a liquid pipeline, and the dent acceptance criteria is somewhat more restrictive. The following is a brief *summary* of the current acceptance criteria for both gas and liquid petroleum pipelines, as well as the required repair procedures.

1.2.1 ASME B31.4 (1992 Edition)

The ASME B31.4 pressure piping code provides for the design, inspection, and operation of liquid transportation systems for hydrocarbons, liquid petroleum gas, anhydrous ammonia, and alcohols. This code defines a dent as a gross disturbance in the curvature of the pipe. A gouge, scratch, or groove is any local disturbance that results in a reduction of wall thickness. The acceptance criteria for dents and gouges is given as:

- Dents which affect the curvature of the pipe at a seam or girth weld must be removed by cutting out the damaged portion of the pipe as a cylinder.
- Dents that exceed 6 percent of the nominal pipe diameter (greater than NPS 4 in size) are not permitted in pipelines that operate at a hoop stress greater than 20 percent of the specified minimum yield strength of the pipe.
- Dents containing a stress concentrator, such as a scratch, gouge, groove, or arc burn must be removed.
- Gouges and grooves having a depth greater than 12.5 percent of the nominal wall thickness must be removed or repaired.

1.2.2 ASME B31.8 (1992 Edition)

The ASME B31.8 pressure piping code provides for the design, inspection, and operation of gas transportation and distribution piping systems. A dent is defined by this code as a depression which produces a gross disturbance in the curvature of the pipe wall. The dpeth of the dent is measured as the gap between the lowest point of the dent and a prolongation of the original contour of the pipe in any direction. A scratch or gouge is defined as a depression that reduces the thickness of the pipe wall. The acceptance criteria for dents and gouges is given as:

- Dents which affect the curvature of the pipe at a seam or girth weld must be removed.
- Dents that exceed 2 percent of the nominal pipe diameter (greater than NPS 12 in

size) are not permitted in pipelines that operate at a hoop stress greater than 40 percent of the specified minimum yield strength of the pipe.

- Dents containing a stress concentrator, such as a scratch, gouge, groove, or arc burn must be removed by cutting out the damaged portion of the pipe as a cylinder.

- Gouges and grooves having a depth greater than 10 percent of the nominal wall thickness must be removed or repaired.

1.2.3 Repair Procedures

The repair procedures for both codes are similar. Scratches, gouges, and grooves may be removed by grinding, provided the wall thickness is not reduced below 90 percent of the nominal wall thickness required for the operating design pressure. When too large a reduction in the wall thickness results, the *damaged* section of pipe must be cut out and replaced, though the ASME B31.4 (liquid) code allows a complete encirclement welded patch. Insert patching is prohibited in both codes. ASME B31.4 (liquid) allows a gouge to be repaired by the use of an approved welding procedure while ASME B31.8 (gas) does not. Any dent which contains a scratch, gouge, or groove must be removed by cutting out the damaged portion of the pipe as a cylinder. Dents without gouges that exceed the specified depths must be removed by cutting out the damaged portion of the pipe as a cylinder. The ASME B31.4 (liquid) code allows for the use of a full encirclement welded or mechanically applied split sleeve.

1.3 DAMAGE TYPES

Indirectly, the ASME dent acceptance criteria classifies dents into two categories: dents with damage and plain dents. The damage that occurs with denting is usually associated with the contact force casing this damage. Different dent formation processes can lead to different dent damage, which in turn will alter the fatigue behavior. Consequently, the type of damage associated with a dent becomes an important criterion for dent acceptance. It is important to note, however, that damage residing in the pipeline that can lead to fatigue failure may not be easily associated with dents. Dent rebound behavior often plays an important role in determining fatigue behavior.

Damage, in the form of dents and gouges, can be introduced into the pipeline at various stages of construction and operation. The following discussion summarizes the possible damage associated with each stage.

Shipment Damage - Damage that occurs during shipment of the pipe from the manufacturer/supplier to the installation site. If pipe segments are improperly secured during transit by either rail or truck, dents and/or fatigue damage may occur. Inadequate support along the pipe length can results in excessive high-bearing forces which in turn cause denting or localized bending. The repeated flexing of the pipe wall at a support point can initiate and propagate a fatigue crack. Once the pipe is offloaded, the pipe wall may return to its original shape making detection of the fatigue damage difficult. It would be expected that any dent formed during shipping would be cause for rejection of the pipe segment unless adequately repaired. Shipping damage occurs most often at the ends of the pipe where, as a minimum, they are supported.

Construction Damage - Dents that occur during construction of the pipeline. These dents can occur from chains or straps used to lift and move the pipe and by earthmoving equipment. Also, they can be caused by pre-existing dents prior to construction which had not been detected or removed. Construction dents can exist anywhere around the circumference of the pipe, but are most prevalent in the upper half of the pipe cross section.

Service Damage - Dents that occur during the service life of the pipeline. The dents are typically from earthmoving equipment and can vary widely in terms of size and severity. These types of dents are always located on the upper portion of the pipe since they are associated with excavation above.

Rock *Damage* - Dents that form due to the pipe being laid on the rock during construction (improper bedding) or settlement of the pipe onto the rock during service. Both local and global bending stresses can result due to the settlement of the pipe (Fig. 1-1). Flexible pipe design requires the consideration of the bending stresses that develop with differential settlement along the pipe. A uniform settlement will not result in bending stresses unless the pipe settles on a rigid object such as a rock. In this case, only localized bending stresses occur in the dent region if the pipe wall is relatively flexible. Differential settlement of the pipe onto a rock or an increase in wall stiffness may result in a superposition of global bending stresses in the dented region. This can lead to altered fatigue behavior.

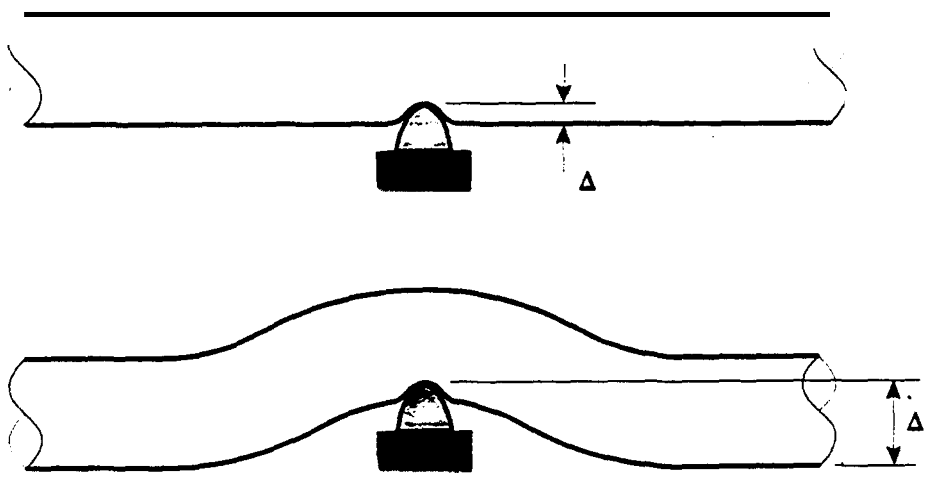

Figure **1-1:** Schema of local and global bending due to pipe settlement on rock.

1.4 DENTING PROCESS

As an object is forced against the outer surface of a pipe, a resistance to this force is developed by internal forces (both plate bending and membrane) in the pipe wall as well as the intemal pressure. If the denting force is sufficient in magnitude, the plate bending moments will cause inelastic behavior due to the yielding of the extreme, outer fibers of the pipe wall. Large bending strains can result in the development of a full plastic hinge at the time of maximum indentation.

The depth of the dent is typically measured in terms of percent pipe diameter or the d/D ratio. This ratio for a given dent will assume several values depending on the stage of the dent forming process. The initial dent depth $(d/D)_{initial}$ is the maximum depth of the dent (in terms of percent). For construction and service dents, this occurs at the maximum application of the denting force. For rock dents, this ratio increases with time as the pipeline continues to settle onto the rock.

The initial dent depth is a function of the internal pressure at the time of the application of the denting force. Higher internal pressures will result in shallower dents for the same denting force magnitude. Construction dents can form in the absence of internal pressure.

Once the denting force is removed, an elastic bound of the dent will occur. .The amount of rebound will be a function of the degree of restraint. Most construction and service dents are unrestrained and can therefore rebound through their fully elastic limit. The rebound dent depth ratio is given as $(d/D)_{rebound}$. The depth will almost never rebound to zero percent since some degree of plasticity will occur at $(d/D)_{initial}$. Rock dents do not rebound unless the pipe settlement is reversed.

The important consequence of the denting process is the residual stress distribution that remains in the pipe wall. The localized stresses, particularly those that are at the outer portions of the wall thickness, will govern the fatigue behavior of the dent since the location of the initial defect for fatigue crack development will coincide. Compressive residual stresses resulting fiom the denting process can will help suppress crack formation. Conversely, tensile residual stresses can accelerate crack growth rates. The dent history then becomes an important consideration for determining dent acceptance. Estimating the fatigue life of a dent using only the final detected depth cannot always provide reasonable predictions.

1.5 OBJECTIVES OF THE STUDY

The primary objective of the current study is to develop a fundamental understanding of the fatigue behavior of dents in pipelines. This will form the basis for the refinement of dent acceptance criteria. Specifically, the following objectives:

- Investigate the fatigue behavior of various dent types to determine if dent parameters in addition to the dent depth need to be considered.
- Investigate the effect of restrain on the fatigue behavior of dents. Restrain limits or prevent rebound under cyclic pressure loading, thus limiting the tensile bending stresses.
- Quantify the fatigue behavior of rock dents. This type of dent has been inadequately studied in the past with regard to cyclic pressure loading.
- Development acceptance criteria based on the finding of the current study in concurrence with past research and standards.

The above objectives will be accomplished by both experimental and analytical studies.

1.6 LIMITATIONS OF THE STUDY

It should be noted that the current research effort was performed with the following limitations:

- Considers the fatigue behavior of dents residing in straight sections of pipe. The additional stresses due to circular bends in pipes are not considered.
- The effect of residual stresses due to manufacturing and welding other than those already within the pipe test specimens.
- Location of dents in relation to welds or seams.
- The mechanical damage process, As discussed, significant localized stresses will occur at the contact region.
- Corrosion effects.

Chapter Two

REVIEW OF EXISTING DATA AND RESEARCH RESULTS

2.1 INTRODUCTION

Prior to the start of the experimental program and the finite element analysis, a review of previous research program results was performed. This provided a basis for the current research and reduced duplicate efforts. Documents reviewed are:

- *Effects of Dents on Failures of Gas Transmission Pipelines,* Urednicek, M., prepared for the Canadian Standards Association Technical Committee, Report No. 14032, September, 1986.

- *Cyclic Pressure Fatigue Life of Pipelines with Plain dents, Dents with Gouges, and Dents with Welds,* Fowler, J.R., Alexander, C.R., Kovach, P.J., and Connelly, L.M., prepared for the Offshore and Onshore Design Applications Supervisory Committee of the Pipeline Research Committee at the American Gas Association, Final Report for PR-210-927 and PR-210-9324, June 1994.

The following discussion summarizes each document as it pertains to the current study.

2.2 CANADIAN STANDARDS ASSOCIATION TECHNICAL COMMITTEE

A review of the acceptance criteria of the Canadian Gas Pipeline Standard (CSA Z184-M1983) was conducted for the repair of gouges, dents, and gouged dents on new gas transmission pipelines under construction. New experimental and field data were analyzed to determine if changes in the acceptance criteria were warranted. The experimental data reviewed included:

- British Gas Corporation - Both plain dents and gouged dents were statically pressure tested to failure in 30 and 36 in. diameter pipe. One plain dent, at d/D = 43%, failed at 60 percent of the yield stress. The remaining plain dents failed at stress levels above nominal yield. The failure stress of the mechanically notched dents were generally below the yield stress in all cases. {Jones 1982}.

- Battelle Columbus Laboratories - Hydrostatic bust tests were conducted on pipes with both plain and gouged dents. Pipe diameters ranged from 16 in. to 42 in. . The location of the dent relative to longitudinal seam welds was examined. Plain dents failed only when located near the weld due to crack formation in the weld during denting. Dents with machined notches generally failed at stress levels below nominal yield. [McClure 1962, Kiefner 1969, Eiber 1981, Mayfield 19791.

- Columbia Gas Company - Five 20 in. diameter pipes with 3 percent dents (*d/D*) were statically pressure tested to failure. In all cases, failure occurred after the nominal yield stress was reached. [Belonos 1958]

- Alberta Natural Gas - Plain dents detected by inspection of in-service pipelines were examined. A total of 46 of the dents was confirmed as rock dents. Ten of the rock dents exceeded the acceptance criteria of 2 percent and were cutout. Two of these were plain dents and were hydrostatically tested to above nominal yield stress levels. Two dents containing gouges at the rock contact region were hydrostatically tested to above nominal yield stress. Four dents contained fatigue cracks that initiated on the inside surface at the dent apex. [Urednicek 19861

- NOVA - Both plain and gouged dents were hydrostatically tested to failure in 36 in. diameter pipe. No failures occurred at stress levels below the nominal yield stress.

The conclusions drawn from this investigation were based on the review of experimental data produced by statically pressurizing pipe section to failure. No cyclic pressure tests were conducted. The conclusions are as follows:

- Plain dents, up to 10 percent of the pipe diameter (O.D.), could remain in service without affecting the pipeline integrity.

- Rock dents behave similar to plain dents. However, crack formation on the inside pipe wall at the dent apex is possible. Inspection to confirm the absence of cracking is required for acceptance.

- Dents with gouges reduce the pipeline integrity, regardless of the dent depth, and should be removed. (No changes to the current criteria were recommended.)

2.3 PRC-AGA RESEARCH PROGRAM

A research program was sponsored by the Pipeline Research Committee (PRC) of the American Gas Association (AGA) to investigate the fatigue behavior of dents in gas transmission pipelines. The research program involved both experimental and finite element analysis of pipes with dents and gouges. The primary objectives of the research program were:

- Determine important variables that govern the fatigue behavior of dents.
- Classification of dents with gouges.
- Investigate influence of weld seam on dent fatigue behavior.

The following briefly summarizes the'methods and conclusions of the research program.

23.1 Experimental Program

The experimental program was divided into the testing of two dent types: plain dents and dents with gouges.

Plain Dents - A survey was sent to 43 oil and gas companies to classify the types of plain dents typically encountered with the operation of a pipeline. While three dent types were determined to be common, only one type was used in the experimental program.. A finite element analysis determined that both the dent type and dent length were not important when considering fatigue behavior. The dents were formed by forcing a 24"x24"x2" flat steel plate oriented flat-wise into the si& of the pipe specimens. The dent length, defined as the distance between two undeformed cross sections adjacent to the-dent, was approximately three times the nominal 12 in. diameter of most of the specimens. The dent depths used, in terms of d/D, were 5, 10, and 20 percent. These depths were measured after the indenter was removed and the dent rebounded. Therefore, the initial dent depth had to be over-estimated by a factor of two. Denting was performed without the pipe specimens under pressure.

The experimental analysis of plain dents was conducted in two phases. The first phase involved eight 12-in. nominal diameter pipe specimens, each 20 ft. long. Varying the wall thickness of the specimens gave a range of D/t from 18 to 50. The dent depths examined were 5, 10, and 20 percent of the nominal pipe diameters. The second phase of testing involved two pipe specimens with larger D/t ratios: 64 (D = 12.75 in., and t = 0.2 in.) and 94 (D = 24 in., and t = 0.26 in.). The dent depths examined were 5, 10, 15 percent for the 12-in. pipe and 5 and 10 percent for the 24 in. pipe.

Each specimen was first statically pressurized to a maximum. of 1200 psi. for the specimens in the first phase and 400 and 900 psi. for the 12 in. and 24 in. pipe specimens, respectively, in the second phase. Dents in the thinner-walled pipe specimens popped-out or removed but remained unchanged in the thicker pipe specimens.

Cyclic pressure testing involved a two-stage pressure range spectrum. Initially, a low pressure range was for a specific number of cycles. If failure did not occur, a higher pressure range was used until failure occurred or 100,000 total pressure cycles had accumulated. The actual pressure range and number of cycles for each varied from specimen to specimen.

Dents with Gouges - Since earlier research indicated that dents with gouges were more critical than plain dents, a second series of testing was performed. Five specimens with nominal diameters of 12 in. were used. Wall thicknesses ranged from 0.22 to 0.51 for a range of D/t of 25 to 58. An easily reproduced machined groove with a radius of 0.002 in. was used to simulate the gouge. A 16 in. longitudinally oriented gouge was first machined into the pipe specimens at various depths. The specimen was then dented using the Same process as with the plain dents. As with the plain dents, a two-stage pressure cycle spectrum was used. The influence of the seam weld location relative to the dents was also investigated.

2.3.3 Finite Element Analysis

Both elastic and elasto-plastic finite element analyses were performed with the primary objective of determining stress concentrations for dents. These stress concentration factors could then be used in analytical fatigue analyses.

The elastic analysis involved the use of three-dimensional models using elastic shell elements. Pipe sizes with *D/t* ratios of 18 to 50 were modeled. The models were generated for a specific dent shape. Indentation was not modeled elastically. Zero residual stress was given to the model with the dented shape. The models were analyzed with internal pressures of 500 psi and 1200 psi. The stresses for the models with *D/t* = 50 with large dent depths were beyond the yield strength of the pipe. Elastic modeling was found to overestimate the stress distribution.

Elasto-plastic modeling is needed since the material yields. Residual stresses also should be accounted for. The modeling needs to include the denting process to account for this. The limitations of the elastic model were studied using the elasto-plastic *two* dimensional models. Elasto-plastic three dimensional models were not studied.

Elasto-plastic analysis was performed on two dimensional rings comprised of shell elements. The objectives of the elasto-plastic analysis were to determine stress vs. pressure data for fatigue calculation and to examine the dent removal caused by pressurization. Support conditions were provided to simulate the denting process for the test specimens. A saddle was used to support the model. The indenter plate was simulated to form the dents. This model actually represents an infinitely long dent in a pipe not subjected to longitudinal stress. Parameters *studied* included *D/t*, dent depth to diameter ratio *d/D*, yield stress, and pressure. Modeling was performed in three steps - denting, removal of indenter, and pressure cycling. The stress data revealed possible locations of fatigue crack development. The locations were found based on stress levels as well as stress range. The locations found were similar to the failure locations found for the test specimens. The dent removal caused by pressurization was significant for the models. Residual dent depth ratios above 1% were not maintained for values of *D/t* = 50 for any initial dent depth. The final dent depths were smaller than depths from the test specimens.

Stress range data was recorded to perform fatigue calculations for the parameters modeled. Data was tabulated for the ratio of change in stress to change in pressure. This data can directly be used to determine fatigue life. Miner's rule fatigue analysis was used to determine the fatigue life.

The results of the tabulated finite element stress range data show that fatigue life is reduced by increasing dent depth and increasing pipe slenderness. Comparisons between the models and test specimens were made. The predicted cycles until failure for the models were mostly lower than the actual test specimens. A few test specimens failed before the predicted values were reached.

23.4 Conclusions

From both the experimental (plain dents and dents with gouges) and finite analysis, the following conclusions were drawn:

Plain Dents

- Plain dents have longer fatigue lives than dents with gouges.
- Fatigue design life is infinite for plain dents in pipes with D/t less than 30.
- Fatigue failures in plain dents can occur when D/t is greater than 30 and the initial dent depth, d/D is greater than 5 percent:
- Three-dimensional elastic finite element analysis indicated that the dent depth ratio, d/D is an important variable in determining fatigue behavior while the dent length is not.

Dents with Gouges

- Gouges that are 10 percent or more of the wall thickness can result in zero fatigue life.

- Gouges that are 5 percent of the wall thickness may reduce the fatigue life of a dent to 2.5 percent of that of a comparable plain dent.

- Gouges in the absence of dents have longer fatigue lives.

Dents with Welds

- The location of a dent on a longitudinal seam weld did not significantly affect the fatigue behavior of the dent.

- Dents located on girth welds have lower fatigue lives than those located on longitudinal welds.

2.4 REVIEW OF DOCUMENTS PERTAINING TO PIPELINE OPERATIONS

In additional to the review of results from both experimental and analytical research programs, various documents pertaining to the operational reliability of pipelines and specific fatigue failures in pipelines were reviewed. From this review, it became evident that fatigue life estimates for pipeline dents were being based on insufficient information, specifically, the dent history. As discussed in Chapter One, the residual stress distribution that results from the denting process cannot be estimated from the final observed dent depth. Without a fundamental understanding of the denting process, basic assumptions that are made with regard to fatigue life estimates are often suspect. This often resulted in conflicting predictions of fatigue life.

2.5 CONCLUSIONS

From the review of various documents, the following conclusions were reached with regard to the present research effort for the fatigue behavior of dented petroleum pipelines and the need for additional research

- The fatigue behavior of long, plain dents has been adequately examined experimentally by the PRC-AGA sponsored program.

- Additional dent types need to be investigated both experimentally and

analytically. This **includes short dents and dents restrained against elastic rebound.**

- **Denting and dent rebound is an elastic-plastic process. The dent residual stresses as a result of this process are greatly influenced by this process.**

- **Dent stiffness, which influences the denting process and rebound** behavior, **is a three-dimensional phenomenon. A two-dimensional analysis may not yield acceptable results.**

Chapter Three
EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

The objective of the OPS test program was to duplicate the test parameters of the AGA program but with the dents restrained. Therefore, pipe sizes, dent configurations, load pressure histories, and mechanical damage similar to those used in the AGA program (see Sec. 2.3) were used in the OPS test program. A total of fifteen pipe specimens were tested.

3.2 PIPE SPECIMENS

The fifteen water-filled pipe specimens were fatigue tested as summarized in Table 3-1. Pipe diameters ranged fiom 12 in. to 36 in. Both 1/4 in. and 3/8 in. wall thickness were used resulting in a range of diameter-to-thickness (D/t) ratios of 32 to 96. The length of the pipe specimens were 20 ft. for the 12, 16, and 18 in. diameter pipes. To reduce the change in volume due to the internal pressure changes and, hence, the cyclic time required for 100,000 cycles, the lengths of the larger diameter pipe specimens were reduced to 13 ft. for the 24 in. diameter pipe and 10 ft. for the 30 in. and 36 in. pipe. The reduced pipe length facilitated handling of the larger diameter pipe, especially when filled with water. A more detailed description of each pipe specimen and its test parameters is given in the Appendix.

Elliptical (2:1 ratio) end caps were welded on the ends of each pipe using the GMAW process. The pipe sections were ordered fiom the supplier with a beveled cut finish. When necessary, the edge of the end cap was beveled so that any difference in wall thickness between the pipe and end caps was properly transitioned. The welding of the end caps was performed at the Testing, Repair, and Machining Facility at the Riverside Campus of Texas A&M University, as well as a local welding company.

Table 3-1: ***Summary*** of pipe specimen properties.

Pipe Specimen Number	Pipe Diameter *D*	Wall Thickness t, in.	*D/t*	Length	API L2 Grade
1	12	0.375	32	20' - 0"	X 60
2	12	0.375	32	20' - 0"	X 60
3	12	0.250	48	20' - 0"	X 42
4	16	0.250	64	20' - 0"	X 60
5	16	0.250	64	20' - 0"	X 42
6	18	0.250	72	20' - 0"	X 42
7	18	0.250	72	20' - 0"	X 60
8	18	0.250	72	20' - 0"	X 60
9	24	0.250	96	13' - 4"	X 60
10	24	0.250	96	13' - 4"	X 60
11	24	0.250	96	13' - 4"	X 60
12	30	0.375	80	10' - 0"	Gr. B
13	30	0.375	80	10' - 0"	Gr. B
14	36	0.375	96	10' - 0"	Gr. B
15	36	0.375	96	10' - 0"	Gr. B

3.3 DENT TYPES

Three different dent types were investigated in the experimental test program as summarized in Table 3-2. They include a 6 in. long dent with simulated damage (Type A), backhoe dents oriented in both the longitudinal (Type BH-L) and transverse (Type BH-T) directions, and rock dents (Type R). These dent types were selected for the primary objective of investigating short dents and restrained dents. The following describes each dent type in detail.

Table 3-2: *Summary* of dent types for each pipe specimen.

Specimen No.	D/t	Total No. of Dents	Dent Type per Specimen				Type A Gouge
			A	BH-L	BH-T	R	
1	32	6	6				0.05"
2	32	10		10			N.A.
3	48	9			5	5	N.A.
4	64	8	8				0.024"
5	64	9		2	3	4	N.A.
6	72	8	8				scribed
7	72	10		10			N.A.
8	72	8			4	4	N.A.
9	96	4	4				scribed
10	96	5		2	3		N.A.
11	96	4				4	N.A.
12	80	3	3				scribed
13	80	3		3			N.A.
14	96	3	3				scribed
15	96						N.A.

3.3.1 Dents with Machined Damage (Type A)

The first type, designated as Type A, was caused by a 6.0 in. long indenter with round edges. Figure 3-1 provides the dimension of the Type A indenter. This type of dent contained a 5-inch long machined notch in the dent trough, as shown in Fig. 3-2, to simulate the damage typically found in a gouge. Some of the dents were restrained on various pipes to investigate the effect on fatigue behavior.

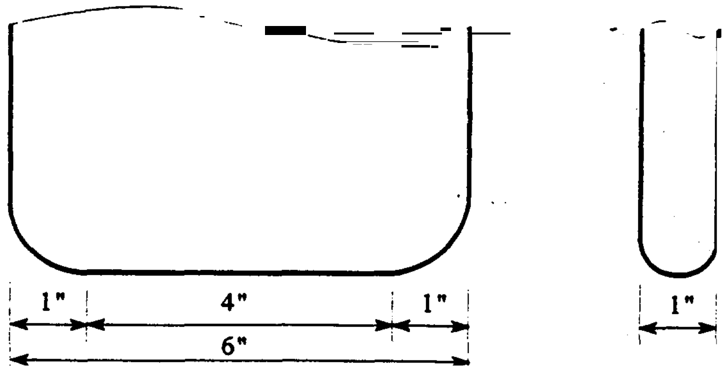

Figure 3-1: Indenter dimensions for Type A dent.

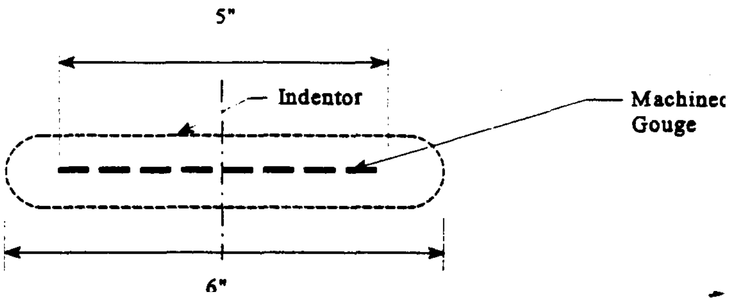

Figure 3-2: Gouge location for Dent Type A.

Various methods were used to simulate the gouge. In the dents of several pipes, the gouge was founded by machining a square-shaped notch using a rotary grinder as shown in Fig. 3-3. This produced a uniform notch to a depth and allowed for reproducible data not influenced by initial defect parameter. In addition, this gouge is similar to that used in other studies and, thus, allowed for the comparison of data. Two gouge depths were used: 0.05 in. and 0.024 in. A portion of a specimen cross section with a machined notch is shown in Fig. 3-4.

It should be noted that this simulation of a gouge will tend to overestimate the resulting fatigue damage since the compressive residual stresses normally associated with the denting and gouging formation are notpresent. Compressive residual stresses reduce the effective stress range and stress intensity range associated with fatigue crack propagation.

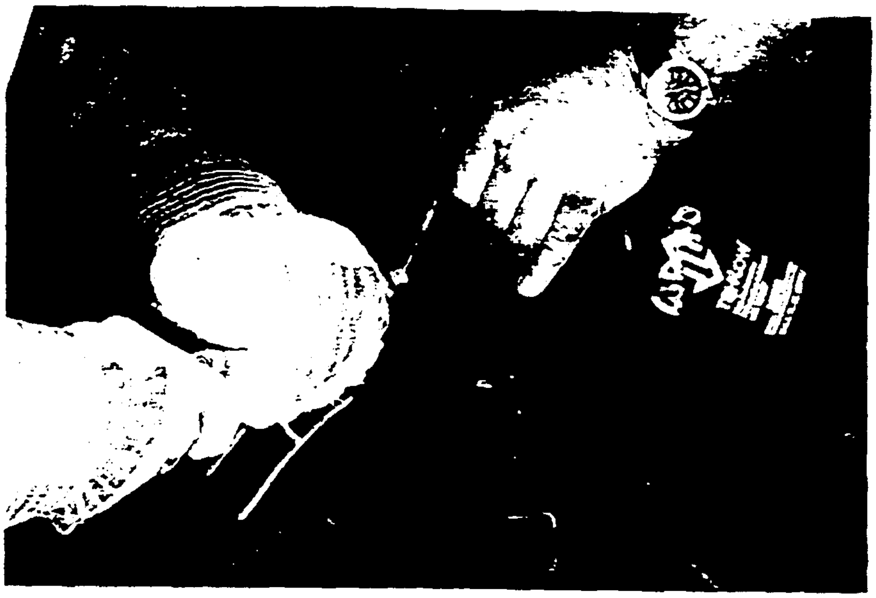

Figure 3-3: View of machining operation for mechanical damage, Dent H, Specimen 4.

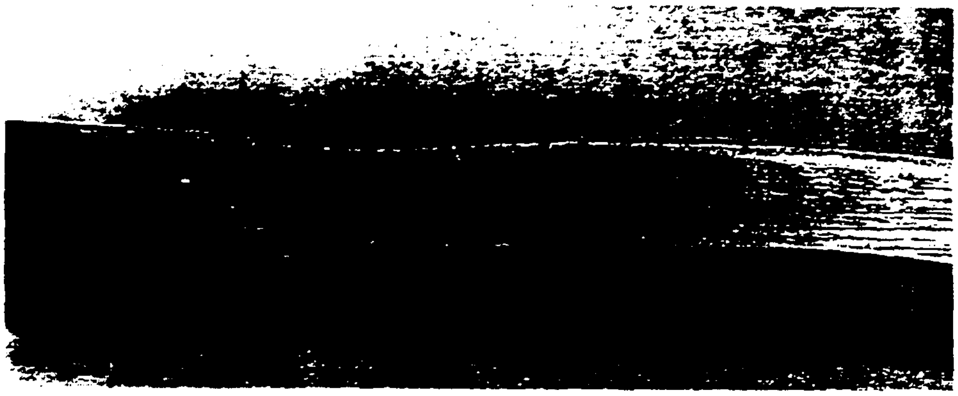

Figure 3-4: *Cross* **section** of Dent C, Specimen 1, **showing** machined notch (d/D = 5%).

In an effort to reduce the severity of the machined notch, the notch in dents of several specimens were manually hammer peened as shown in Fig. 3-5, 6. Preliminary analysis of the data indicates that the peening did not significantly affect the fatigue behavior of the Type A dents. For later specimens, a scratch was formed by manually scribing a shallow notch with a hardened steel scribe, as shown in Fig. 3-6, Three passes were made along a straight-edge for each scratch in an effort to impose some of the compressive residual stresses into the gouge that would be expected if a sharp foreign object is drawn across the surface of the pipe. This dent type was tested in both *the* restrained and unrestrained configurations to investigate the effect of dent rebound on fatigue behavior.

Figure 3-5: Peening of mechanical damage prior to denting, Specimen 4.

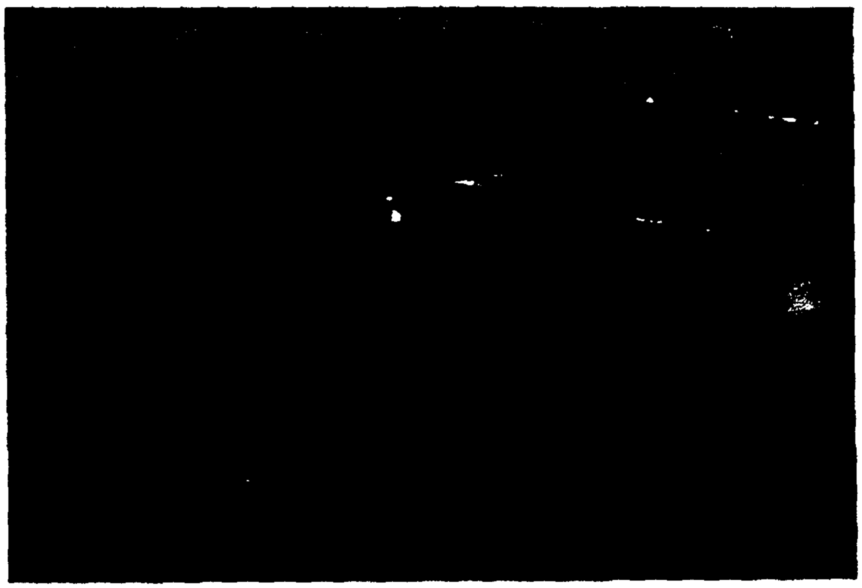

Figure 3-6: Scribing of scratch along straight-edge to simulate damage from moving indenter.

3.3.2 Dents Caused By Backhoe Teeth (Type BH-L & BH-T)

Another type of dent investigated experimentally was formed by forcing a typical backhoe tooth into the wall of the pipe specimens. This resulted in a dent relatively short in length since the backhoe toe was not forced horizontally along the surface of the pipe. Dents with the backhoe tooth oriented (With respect to the longitudinal axis) in both the longitudinal (Type BH-L) and transverse (Type BH-T) direction were used. An example of a backhoe tooth used for this dent type is shown in Fig. 3-7.

Figure 3-7: View of backhoe tooth restraint.

3.3.3 Rock Dents (Type R)

The third type of dent investigated was the rock dent (Type R). This type of dent was formed by forcing the rock into the pipe wall and then restraining the rock in the same position prior to cyclic loading. This allowed for the investigation of dents formed by the pipeline being laid on to a rock during initial construction or by the settlement of the pipeline during service. Figure 3-8 provides a view of a Type R dent showing the rock restrained in a dent.

Figure 3-8: View of restrained rock, Dent F, Specimen 8.

The types of rocks used in the experimental program were selected for their relatively high hardness and compressive strength. Both quartz and flint rocks were used. Each rock was selected for its rounded conical shape. This increased the local curvature of the dent from that of a more rounded or flat-shaped rock.

It should be noted that the actual fatigue behavior of rock dents will be influenced by the strength of the rock. Low strength rocks fail due to high localized compressive stresses at the point of contact with the pipe wall. This will possibly decrease the curvature of the dent and increase the dent fatigue life.

3.4 DENTING

The dents were formed by forcing an indenter perpendicularly *into* the wall of each pipe specimen. The denting was performed in a 500 kips testing apparatus in the Structures Laboratory for the smaller diameter specimens (see Fig. 3-9) or with a portable load frame and actuator at the Riverside Campus for the larger diameter specimens (see Fig. 3-10).

Figure 3-9: View of **denting process in 500 kip testing apparatus, Specimen 7.**

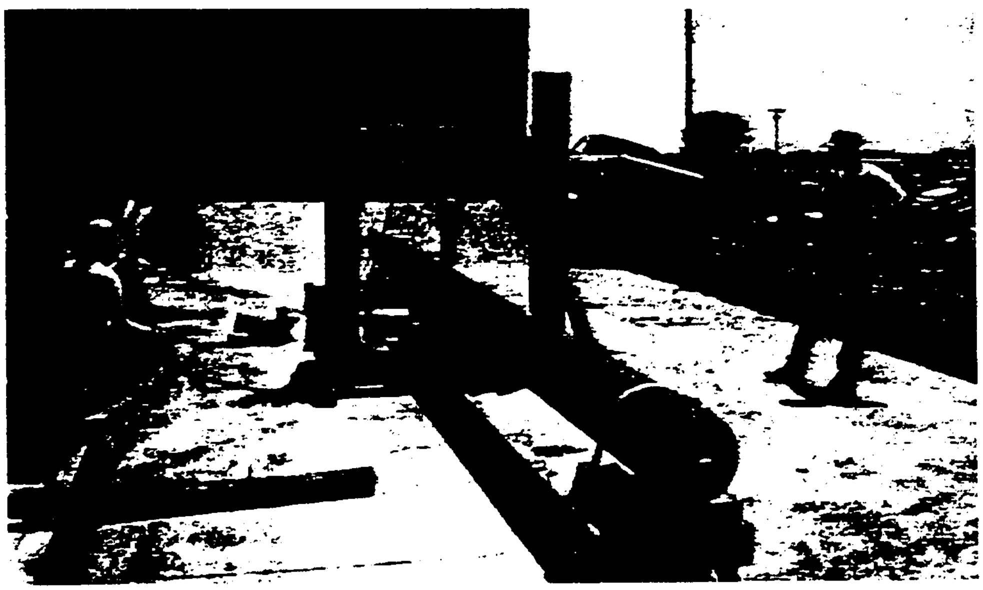

Figure 3-10: View of denting process with **portable load frame, Specimen 3.**

For each dent type used on a particular specimen, different initial dent depths were used. as summarized in Table 3-3. The initial dent depths, given in terms of the percentage of nominal diameter. ranged from 5 to 18.75 percent. The actuator forces required to attain the initial depth were measured for each dent and are summarized in Appendix A. It should be noted that with the removal of the indenter, elastic rebound of the dent occurred. Consequently, the final depth was always less than the initial depth. The degree of elastic rebound is a function of the diameter. thickness, and the dent type.

The indenter used to force the dents varies with the dent type. The Type A indenter. as shown in Fig. 3-11, was centered over the dent location so that the machined gouge would reside in the dent trough. Figure 3-12 shows the same dent as formed in Fig. 3-11. Note that majority of the plastic deformation in the pipe wall from the indenter contact is at either end of the dent. Consequently, crack initiation would be expected to be more towards the center of the dent, removed fiom regions of compressive residual stress.

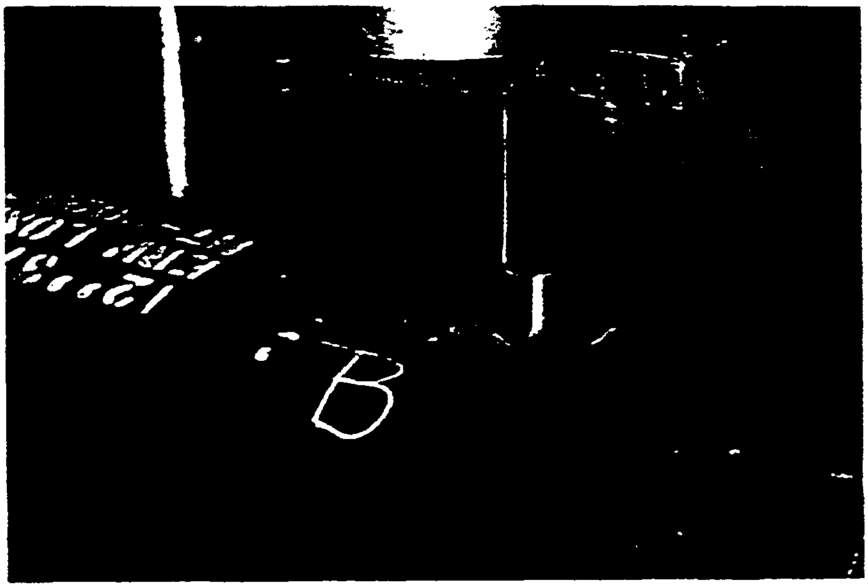

Figure 3-11: Indenter Type A at maximum depth for Dent B, Specimen 1.

Table 3-3: ***Summary*** of dent depths (d/D) by specimen **and** dent type.

Type A															
5.0	2			2		2			2			1		1	
7.5						2			2			1			
10	2			2		2			2			1		1	
12.5															
15	2			2		2								1	
17.5															
18.75				2											
Type BH-L															
5.0										1			1		1
7.5		2					2						1		
10		2			1		2			1			1		1
12.5		2					2								
15		2			1		2								1
17.5		2					2								
Type BH-T															
5.0			1		1					1					
7.5			1							1					
10			1		1					1					
12.5			1					2							
15			1		1			2							
17.5															
Type R															
5.0			1		1						1				
7.5			1		1			2			1				
10			1		1			2			1				
12.5			1								1				
15					1										

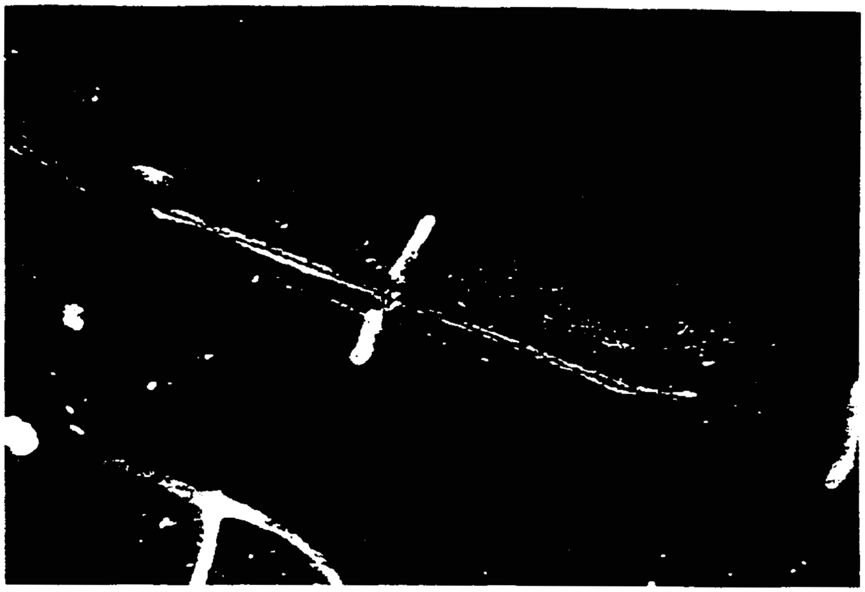

Figure 3-12: View of Dent B, Specimen 1, after removal of indenter and prior to testing.

Figure **3-13** provides **an** example of a backhoe tooth used for the Type BH (L & T) dents. Figure 3-14 shows the same **type** dent after removal of the backhoe tooth. Note the impression of the backhoe tooth left in **the** pipe wall indicative **of** plastic **flow** and deformation. High residual stresses would be expected in this region. Consequently, fatigue crack initiation would be suppressed.

Figure 3-13: Indenter for dent Type **BH-L** at maximum depth for Dent **A,** Specimen **7.**

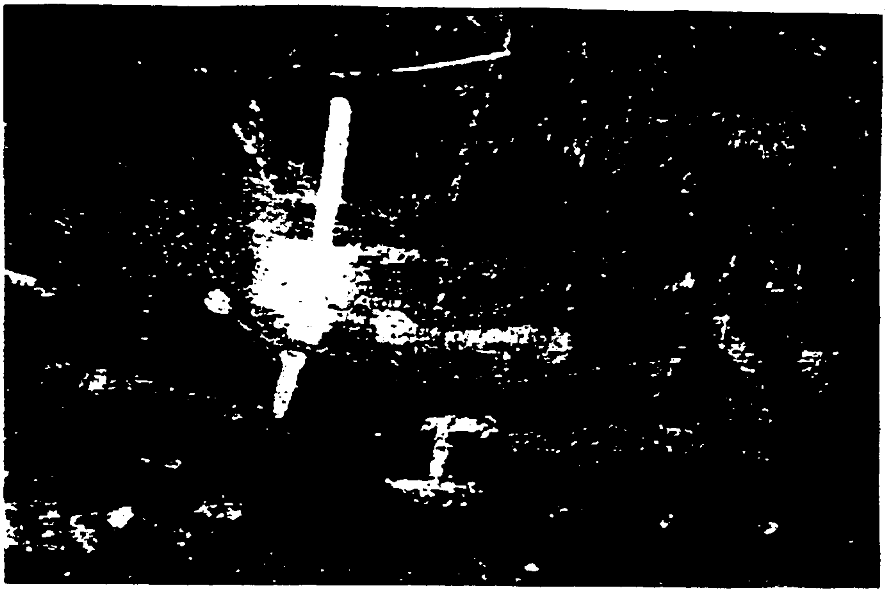

Figure 3-14: View of Dent Type BH-L after removal of indenter and prior to testing (Dent I. Specimen 1).

The Type R dents were formed by forcing the rocks into the wall of the pipe specimens, as shown in Fig. 3-15. The same rock used as the indenter was also used during fatigue testing so the same contact forces developed at the same locations in the dent. Several of the rocks failed by tensile splitting during the denting process.

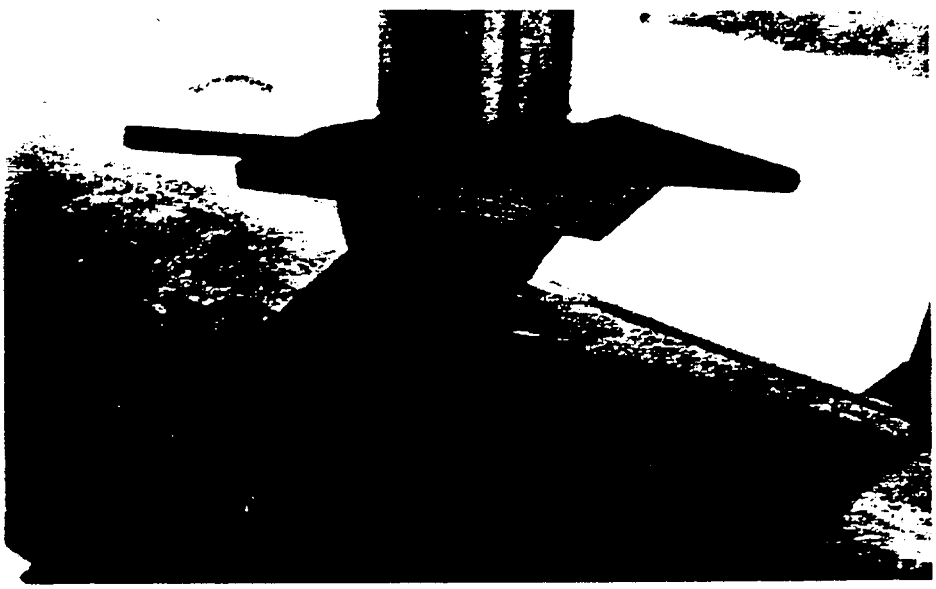

Figure 3-15: Rock indentation, Specimen 3.

3.5 RESTRAINT

In order to investigate the effects of restraint on the fatigue behavior of dents, the indenter devices were held against selected dents of each pipe specimen while the pipe was cyclically tested. When a dent resulting fiom a backhoe tooth was restrained, the same tooth was used for both denting and restraining. Likewise, the same rock was used for both denting and testing. This insured that the dent profile remained unchanged. The 6 in. long indenter used with the Type A dent is shown attached to a small section of pipe in Fig. 3-16.

The typical assembly shown in Fig. 3-16 was then placed in the dent and held in place using several industrial tie-down straps. These straps are typical of those used to secure cargo on flatbed tractor trailers and can be tightened to various degrees through the use of a ratchet system. Prior to the start of the fatigue test program, these straps were proof tested to approximately 11,000 lbs. Since each strap looped around the pipe in a continuous fashion, a resisting force of approximately 20,000 lbs for each strap was possible. In order to attenuate the strap-bearing forces around the pipe, 1"x2" wood strapping was used between the straps and pipe. Figure 3-17 shows Specimen 4 with Dents E through H restrained using the indenter and strap system. Figure 3-18 shows a restrained Type A indenter in contact with the dented pipe.

Figure 3-16: View of 4" dent restraint (Type A).

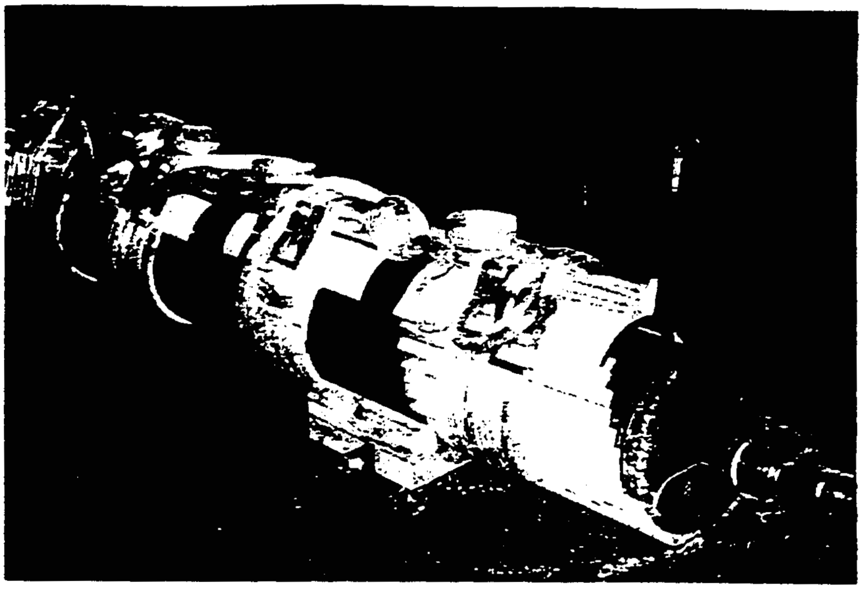

Figure 3-17: View of Specimen 4 with **restrained Dents** E **through H.**

Figure 3-18: Close up view of restrained Type **A dent (Dent E, Specimen 4).**