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STRENGTH CHARACTERISTICS OF JOINTED WATER PIPELINES

By

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INTRODUCTION

The present report has a three fold purpose:

a. To give a general description of a typical pipeline network, with particular emphasis on its geometric configuration and physical characteristics.

b. To describe the strength properties of typical pipeline materials and the materials used in their joints, to give a resume of test data on pipeline joints and to try to correlate the test data with the results of elementary theory.

c. To describe standard pipeline design methods, to present typical pipeline modeling data and to derive the needed typical entries for a static "failure matrix," which establishes failure characteristics for various types of pipelines, depending on their geometric configuration, their materials, the materials of their joints, and their support, operating and loading conditions.*

This report is the result of a thorough survey of the literature on underground water pipes, but aims at establishing a static "failure matrix methodology" rather than at presenting the application of such methodology to a complete set of pipeline types. Therefore, most of the data and examples are limited to cast-iron pipes of diameters between 4 in. and 36 in. under static conditions.

The report also contains recommendations for additional tests on pipeline joints to complement the scant data available at the present time.

*The failure matrix takes into account both the failure of the pipes and that of the joints, giving conditions for both material failure and leakage.

The operating pressures in transmission or distribution systems are determined by the amount of water to be transported and by factors such as:

a) the capacity of the pumping equipment,

b) the gravity gradient due to the site topography, and,

c) the pressure-flow characteristics of the valves and control equipment.

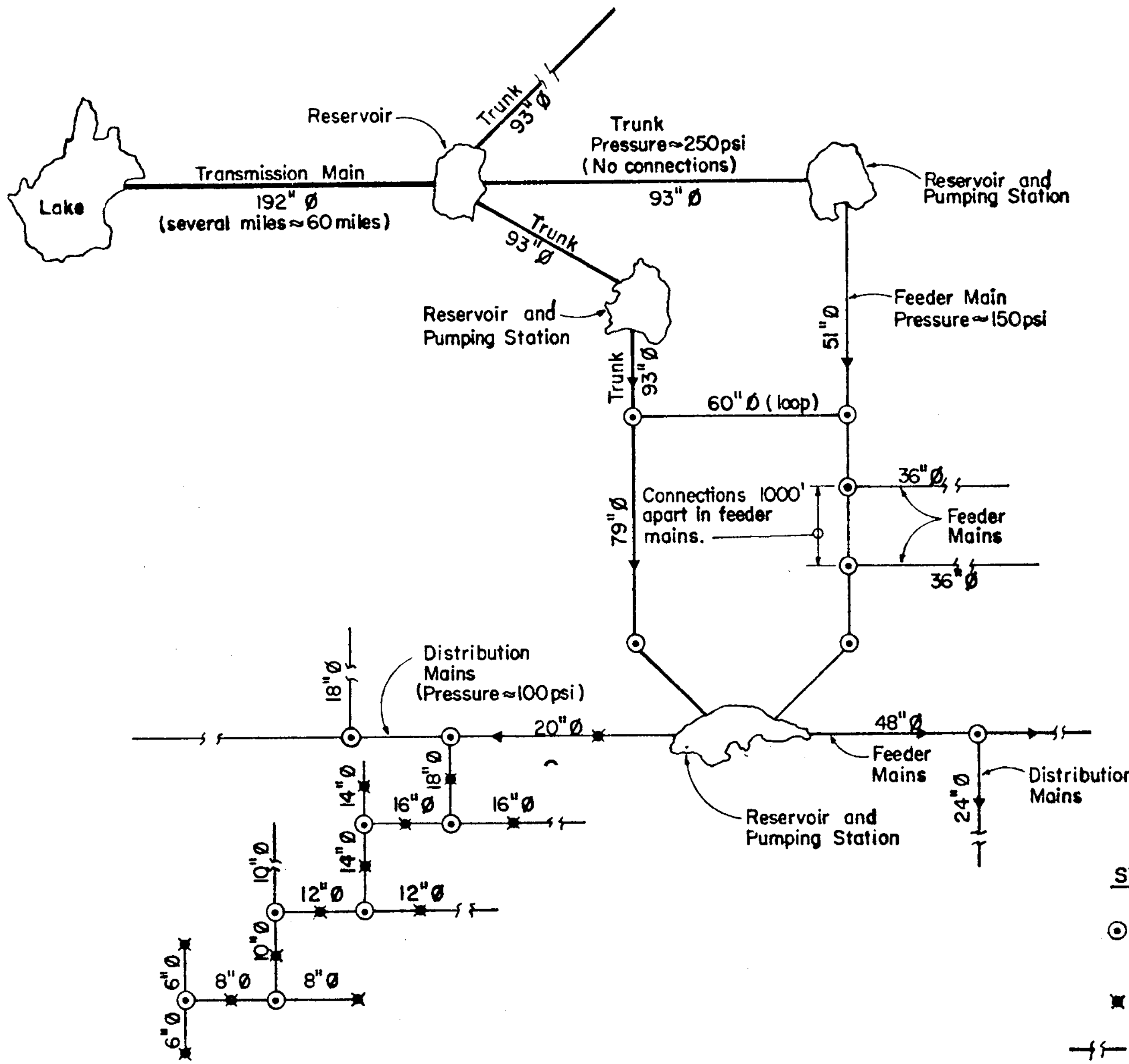
b. Pipe Support Condition

Water pipes are supported in a variety of ways depending largely upon soil conditions, overall site topography and construction considerations. Water pipes crossing fields and other open areas, as well as those under highways and airport embankments, are usually placed in earth trenches. Following the American National Standard Institute Code A 21-50, pipe laying conditions in trenches, under embankments or in tunnels have been standardized and classified as Types 1 through 5. The difference between the 5 types of laying conditions depend on the compaction level of the soil surrounding the pipe and on whether bedding is provided under the pipe to support it.

The support conditions control the stress distribution in the pipe due to the various loads on it, such as the earth pressure and the truck superimposed loads. They also affect the deformations of the cross section of the pipe and its longitudinal deformations, if any.

The earth pressure on pipes laying in trenches and under embankments in silty-clay type soils depends on soil settlements and on arching effects. These in turn depend on the relative stiffnesses of the pipe to that of the soil surrounding the pipe.

Fig. 1 **SCHEME OF WATER DISTRIBUTION SYSTEM**



Notes:

- Distribution mains are the most costly single item in water works system.
- Trunk, Transmission and Feeder mains are 20"-200" in diameter; 20"-48" Ø are the most commonly used.
- Distribution mains are 2"-24" in diameter; 8"-16" Ø are the most commonly used.
- Few or no connections are permitted in transmission mains with operating pressures higher than 250 psi.
- On Feeders with pressures of 150-200 psi, the distribution connections are permitted at spacings of not less than 1000'.

SYMBOLS:

⊙ Anchorages and valves

✱ Service connections

—⟊— Pipeline to continue

Ø Diameter of pipeline

Part I: Pipeline Network Description

a. Typical Overall Configuration

A survey of the various types of pipes used in water supply systems has been conducted and a summary of it is given in this section.

Transmission trunk or feeder mains of diameters 20"-200" are commonly used to transport large amounts of water from water supply sources, such as lakes or rivers, to large water reservoirs and treatment plants. The mains operate most frequently under a 100-250 psi pressure due to either hydraulic pumps or to differences in elevation. These transmission mains have lengths varying from a few to many tens of miles. After suitable treatment to control turbidity and/or bacteria levels, the water is pumped from city reservoirs to the supply mains via medium size distribution mains with diamaters of between 6"-24".

A typical water supply system is shown in Fig. 1, which identifies transmission, feeder, trunk and distribution mains, service connections, and other network details.

At all points where the water lines change direction, as well as at branching points, suitable thrust blocks, anchor blocks or tie rods are provided to counter the forces exerted on the pipeline by the water flowing under pressure through it.

Design and manufacturing difficulties are encountered in control valves which operate at pressures equal to or higher than 250 psi. Consequently, only very few and often no connections are permitted in transmission mains which operate at pressures higher than 250 psi.

Figure 2 summarizes standard laying conditions:

1. in trenches,
2. under embankments,
3. in tunnels, and
4. over-ground.

In addition to being layed in one of the above 4 conditions pipes may also be supported in special ways, such as on cables or underwater.

c. <u>Water pipe and Joint Materials and Characteristics</u>

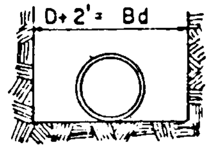
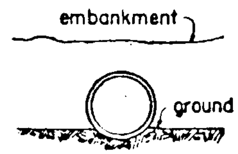
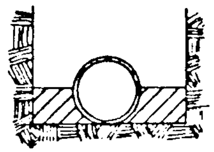
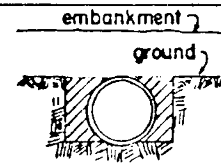
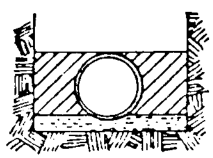
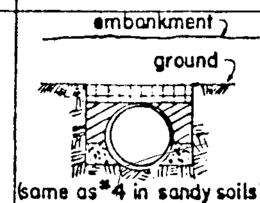
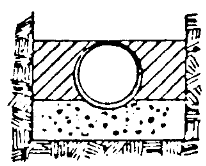
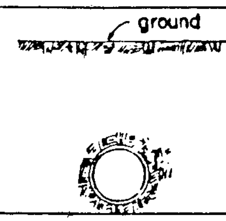
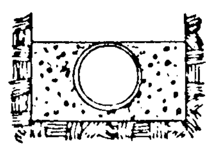
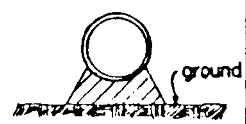
At least 10 different types of materials are commonly used for the pipes in the 3 basic types of lines:

1. the transmission, feeder & trunk mains,
2. the distribution mains, and
3. the service connections.

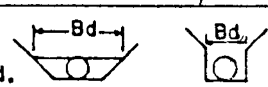
Various pipe characteristics, including their material properties are summarized in Table I.

The different types of water pipes are governed by various national specifications and codes. In particular, Table II lists types of metals and applicable specification numbers.

Fig 2 STANDARD LAYING CONDITIONS (REF #12, #18, ANSI A21.50)

TYPE	TRENCH TYPE	DESCRIPTION	TYPE	EMBANKMENT AND TUNNELS	DESCRIPTION (Ref. 1)
1		Flat bottom loose backfill	I		Embankment positive projection
2		Flat bottom backfill lightly consolidated to ℄ pipe	II		Embankment neutral projection
3		Pipe bedded in 4" loose soil. Backfill lightly consolidated to top of pipe.	III		Embankment negative projection (Earth pressure for this case is different than in case #4 due to settlement caused by embankment and super loads.)
4		Pipe bedded in sand, gravel or crushed stone to depth of 1/8 pipe diameter, 4" min. backfill compacted to top of pipe.	IV		Tunnel or thrust bore
5		Pipe bedded in compacted granular material to ℄ of pipe. Compacted granular material to top of pipe.	V		Elevated and over ground (Out of scope of N.S.F. study)

NOTES:



- Trench width at pipe, top is always used.
- Most common earth cover depth is 3'-6" to 8'-0" in sandy soils.
- Most common earth pressure + super loads is ~15 psi.

TABLE I **PRESSURIZED UNDERGROUND WATER PIPE LINES (cont.)** 1/3

Type of Pipe	Most frequently used by utilities for:	Designed pressure range (psi)	Most commonly used pressure range (psi)	Available pipe diameters (in.)	Most frequently used diameter sizes (in.)
Asbestos Cement	Distribution mains	100-200	100-150	3-36	6-20
Reinforced Concrete	Low pressure & gravity transmission & feeders	50-55	50-55	12-144	16-96
Steel Prestressed Concrete	Trunk mains Distribution mains	100-250	150-250	16-48	16-48
Embedded Steel Prestressed Concrete	Trunk Mains Distribution Mains	100-350	150-350	24-200	24-96
Cast Iron	Distribution mains	50-350	50-150	3-48	8-24
Ductile Cast Iron	Distribution mains	100-350	100-200	2-54	8-24
Mild Steel	Trunk lines Distribution mains with pipes over 16" in diam.	100-350	150-350	4-144	16-60
High Tensile Steel	Main feeders	150-350	150-350	6-42	9-30
P.V.C.	Distribution mains & service systems	100-300	100-150	0.5-12	0.5-6

TABLE I **PRESSURIZED UNDERGROUND WATER PIPE LINES (cont.)**

Pipe Lengths (Ft.)	Most Common Length (Ft.)	Pipe Thickness Range of Most Frequently used Pipes (in.)	Most Common Types of Joints	Type of Internal Lining & Thickness (Ref 13,14)
10-13	10	0.32-4	Poured-cement gasket	None
8-24	16	2-8	Gasket sleeve coupling	None
6-16	16	Cylinder 18 Gauge steel	Gasket sleeve coupling	None
6-16	16	Cylinder 18 Gauge steel	Gasket sleeve coupling	None
12-20	20	0.4-1.07	Push-on bell-&-spigot Mechanical	Coal tar Plastics
12-20	20	0.27-0.56	Push-on bell-&-spigot Mechanical	Coal tar Plastics
20-40	20	0.25	Welding mechanical	Cement Mortar (1/16"-1/2") Coal tar (3/32")
20-60	40	0.134-0.312	Welding mechanical	Cement Mortar (1/16"-1/2") Coal tar (3/32")
20	20	0.109-0.4	Sleeve coupling Push-on jointing compound	None

TABLE I **PRESSURIZED UNDERGROUND WATER PIPE LINES**

Strength of Materials (Ref. 1 - p.223) (Poisson's Ratio .2 - .38)			Most Commonly Laying Condition	Design Criteria & Methods	Ref. No.	Type of Pipe
Modulus of Elasticity X10^6(psi)	Yield Stress (psi)	Ultimate Strength(psi)				
3.5	2500	3000	1,2,3 I,II,III	Flexible Pipe Design Designed for independent loading conditions.	2	Asbestos Cement
3	300	500	3,4,5 I thru V	Flexible Pipe Design 3 Load Conditions, (3rd Condition is DL + LL without internal pressure and 1.8 load factor on ultimate strength)	3 11	Reinforced Concrete
2 - 6	Prestress Dependent	Prestress Dependent	3,4,5 I thru V	Rigid Pipe Design Cubic Parabola interaction curve	4	Steel Cylinder Prestressed Concrete
2 - 6	Prestress Dependent	Prestress Dependent	3,4,5 I thru V	Rigid Pipe Design Cubic Parabola Interaction Curve	4	Embedded Steel Cylinder Prestressed Concrete
15	22000	23000	1,2,3 I,II,III	Rigid Pipe Design Quadratic Parabola Interaction Curve	5	Cast Iron
24	42000 (Bending Tensile Yield 72000)	60000 (Min. Elongation = 10%) (Bending Ultimate 96,000 psi)	1,2,3 I,II,III	Flexible Pipe Design Separate Design For Internal & External Loads	6 12	Ductile Cast Iron
31	30000	48000	3,4,5 I thru V	Flexible Pipe Design	7,8	Mild Steel
31	240,000	250,000	3,4,5 I thru V	Flexible Pipe Design	7	High Tensile Steel
.1	700	3500	1,2,3 I,II,III	Flexible Pipe Design	9,10	P.V.C.

Table II - List of Material Specifications

Material	
Copper pipe	ASTM B42
Red brass pipe	ASTM B43
Cast iron, bell-and-spigot	FSB WW-P-421
Cast iron, pit cast	ASA A21.2
Cast iron, centrifugally cast in metal molds	ASA A21.6
Cast iron, centrifugally cast in sandlines molds	ASA A21.8
Welded wrought-iron pipe	ASTM A72
Welded and seamless steel pipe	ASTM A53
Seamless carbon-steel pipe	ASTM A106
Black and galvanized welded and seamless steel pipe	ASTM A120
Electric-fusion-welded steel pipe (30 in. and over)	ASTM A134
Electric-resistance-welded steel pipe	ASTM A135
Electric-fusion-welded steel pipe (4 to 30 in.)	ASTM A139
Seamless and welded austenitic stainless steel pipe	ASTM A312
Spiral-welded steel or iron pipe	ASTM A211
Line pipe	API 5L

Cast iron, concrete and steel pipes are the main types of pipes commonly used in water supply systems. Small plastic pipes are being introduced in some of the new service connections, while some of the older systems still have wooden pipes. For the domestic water supply, the use of copper pipes is common. Most of the water pipes are designed for an operating pressure in the range of 50 to 250 psi, with a surge allowance of approximately 100 psi. The water pipes are transported to the job site in the lengths of 20-40 feet and are joined together most often by "flexible joints." In steel pipes,however, welded connections are also common. Thus, except for welded steel pipes, water pipelines behave mostly as a flexible chain with rigid links and weak joints, permitting most of the deflections to take place in the vicinity of joints. Most of the new construction in water supply systems uses a push-on type rubber gasket joint, which is a truly flexible joint and permits large structural deformations in an earthquake environment.

All steel, cast-iron and ductile cast-iron pipes are lined with cement mortar or coal tar to prevent excessive corrosion. Since in steel pipes the protection against corrosion is absolutely necessary, these pipes are coated both on the inside and the outside.

d. Water Pipe Earthquake Breakage Statistics

Experience gained from many different earthquakes around the world has shown that considerable damage due to earthquakes occurs to underground water pipelines.

Table III summarizes available data on the observed pipe breakage during earthquakes in the San Fernando Valley, California and in Kanto and Niigata (Japan). For example, in the February 1971 San Fernando Valley earthquake in an area containing 300 miles of 8"-30" cast-iron and steel pipes, there was a total of 829 main breaks, 27 pipe ruptures and 647 service breaks, i.e., a total of 1,503 failures in 300 miles length of pipe or a damage/mile ratio of 5.01. A list of the 27 main breaks in the 1971 San Fernando Valley, California earthquake are shown in Table IV. Similarly, for the Kanto earthquake in the city of Yokohama, Japan the damage/mile ratio was 15.8, while for the Niigata earthquake the ratio was 3.84. It is obvious that the damage/mile ratio depends upon several parameters, including:

- soil type and conditions
- pipe support condition
- pipe material
- diameter and thickness of the pipe
- duration of the earthquake
- magnitude and characteristics of the earthquake

Some suggestions for earthquake proofing of lifelines are made in Figure 3, where it is emphasized that the pipelines joints, connections, branches, and locations of pipeline size-changes or direction-changes, require special consideration, as most of the earthquake structural damage or pressure leakage occur at these points.

TABLE III SOME TYPICAL EARTHQUAKE WATER PIPE BREAKAGE STATISTICS

Earthquake Description	Location	Pipe Length	Type of Pipe	Diameter of Pipes	Total Number of Main Breaks	Total Number of Service Breaks	Total Damage/Mile	Ref. Number
San Fernando 9 Feb. 1971	San Fernando Calif.	300 Miles	Cast Iron Steel Asbestos	8"-30"	829+27	647	5.01	16
Kanto	Tokyo	-	Cast Iron	-	-	-	4.1	17
Kanto	Tokyo	-	Steel	-	-	-	1.51	17
Kanto	Yokohama	-	Cast-Iron	-	-	-	15.81	17
Niigata	Niigata	-	Steel	-	-	-	1.42	17
Niigata	Niigata	-	Cast-Iron	-	-	-	3.84	17
Non Earthquake (ordinary) Breakage 18 cities in Illinois & Wisconsin.			Cast Iron	Mostly 4"-8"	-	-	0.0076	17

TABLE IV MAIN BREAKS IN 1971 SAN FERNANDO VALLEY EARTHQUAKE

(Select Area East Valley District)

(Ref. 29)

No.	Size	Type of Pipe	Joint Type	Location	Nearest Intersection Streets	Date Installed
1.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Coldwater Canyon	1929
2.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Coldwater Canyon	1929
3.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Ethel	1929
4.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Ethel	1929
5.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Ethel	1929
6.	6"	C.I.	C.C.	Fulton Ave. - 12' W ¢	Bloomfield	1925
7.	4"	C.I.	C.C.	Longridge Ave. - 11' W ¢	Moorpark	1927
8.	6"	S	C.C.	Fulton Ave. - 5' W ¢	Moorpark	1932
9.	8"	C.I.	C.C.	Moorpark St. - 22' S ¢	Fulton	1937
10.	8"	C.L.W.S.	W	Valley Heart Dr. - 18' S ¢	Matilija	1965
11.	6"	S	C.C.	Ventura Blvd. - 35' N ¢	Tyrone	1929
12.	6"	C.I.	C.C.	Dickens St. - 10' S. ¢	Van Nuys	1924
13.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Van Nuys	1929
14.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Vesper	1929
15.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Vespter	1929
16.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Cedros	1929
17.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Kester	1929
18.	6"	S	C.C.	Ventura Blvd. - 42' N ¢	Lemona	1929
19.	6"	C.I.	C.C.	Saloma Ave. - 12' S ¢	Ventura Freeway	1960
20.	6"	S	C.C.	Greenleaf Ave. - 4' S ¢	Sepulveda	1928

For Nomenclature for Type of Pipe and Joint Type, see page 18.

Main Breaks 1971 Earthquake - 2

No.	Size	Type of Pipe	Joint Type	Location	Nearest Intersection Streets	Date Installed
21.	6"	S	C.C.	Woodcliff Rd. - 14' W ¢	Del Gado	1929
22.	6"	S	C.C.	Woodcliff Rd. - 14' W ¢	Del Gado	1929
23.	6"	S	C.C.	Woodcliff Rd. - 14' W ¢	Del Gado	1929
24.	6"	S	C.C.	Woodcliff Rd. - 14' W ¢	Rayneta	1929
25.	16"	C.I.	C.C.	Rayneta Dr. - 7' S ¢	Saugus	1954
26.	16"	C.I.	C.C.	Rayneta Dr. - St. ¢	Cody	1954
27.	6"	S	C.C.	Valley Vista Blvd. - 13' S ¢	Kester	1926

Nomenclature for Type of Pipe and Joint Type

S - Denotes Steel Pipe

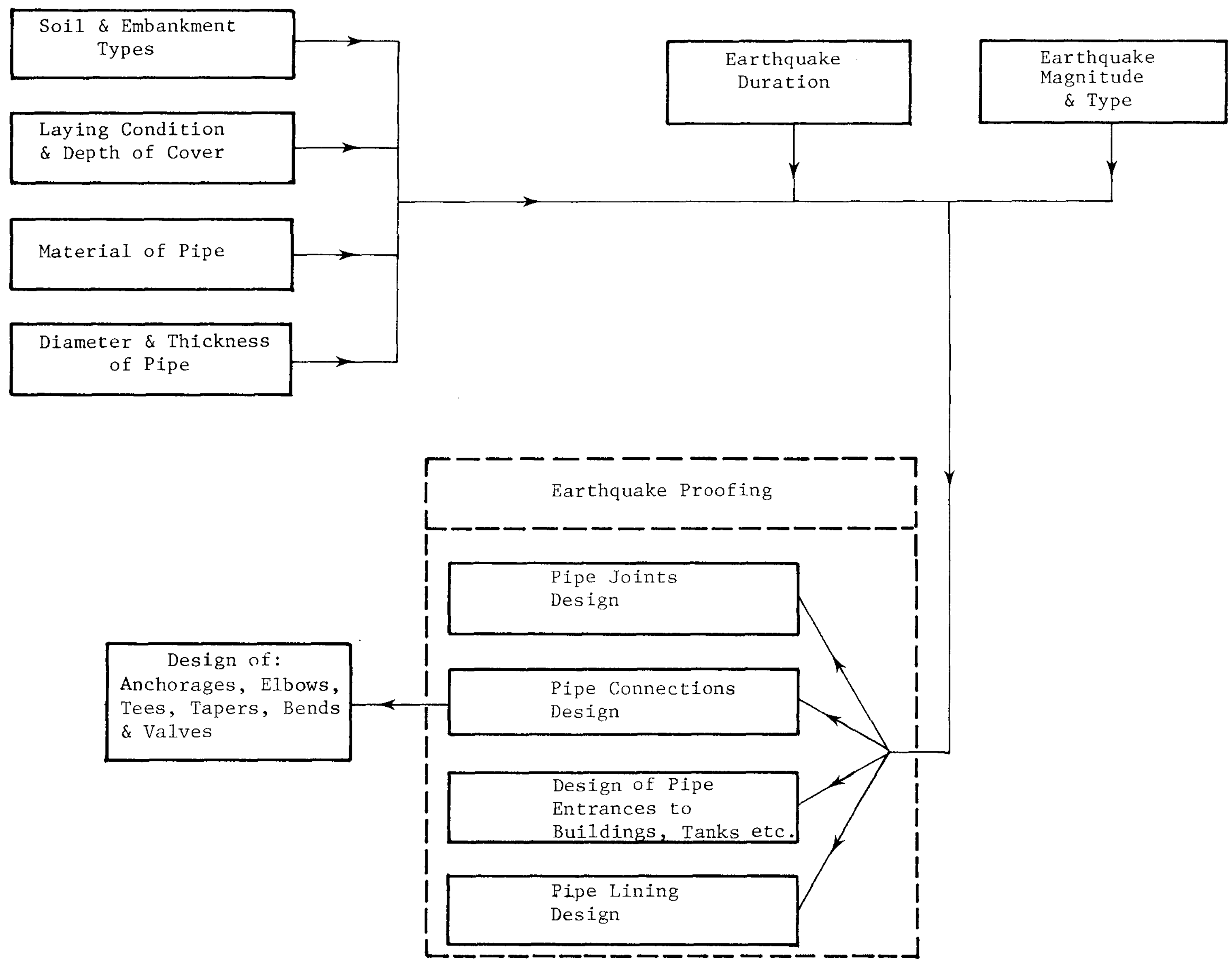
C.I. - Denotes Cast Iron Pipe

C.L.W.S. - Denotes Cement Lined Welded Steel

C.C. - Denotes Cement Caulked Joint

W - Denotes Welded Joint

Fig. 3 **EARTHQUAKE CONSIDERATIONS ON PRESSURIZED UNDERGROUND WATER PIPES**



Tests carried out on cast-iron pipe joints by Professor Prior at Ohio University (1933) and on cast-iron soil-pipe joints by Professor Sanders at Iowa University (1970) (see Part II, section f.2) have shown that pipe joints lead to lower leakage if:

1. The internal water pressure is low (although sometimes at higher internal pressures, joint inter-locking may take place),
2. Rubber-gasket flexible joints are used.

In addition, these studies show that care should be taken to adequately design connections and branches, where stress-concentration can develop stresses 10-12 times higher than in the pipe. (High bending stresses at the boundary points, such as connection or branch points, are responsible for these stress concentration factors.)

e. PART I - REFERENCES

1. Stephson, David, "Developments in Water Science - Pipeline Design for Water Engineers," Elsevier Scientific Publishing Company, Amsterdam, Netherlands, 1976.

2. Johns-Manville, "Transite Ring-tile Pressure Pipe - Installation Guide,", 1969.

3. AWAA Standard - E302-74, Reinforced Concrete Pressure Pipe, Noncylinder Type for Water and Other Liquids. (1974)

4. AWAA Standard - C301-72, Prestressed Concrete Pressure Pipe, Steel Cylinder Type for Water and Other Liquids, 1972.

5. ANSI A21.1 - Standard for Thicknass Design of Cast Iron Pipe (1967).

6. ANSI A21.51 - Centrifugally Cast - Ductile Iron Pipe Metal, Sand-Lined Molds - Water (1971).

7. Naylor Spiralweld Pipe Systems, Lockseam Spiralweld and Spiral Buttweld Pipe, Fittings, Flanges and Connections, Chicago, Illinois, Bulletin SP.

8. Committee on Pipeline Planning, "Pipeline Design for Water and Waste Water," ASCE, 1975.

9. Johns-Manville, "Ring Tite PVC Pipes - Installation Guide" 1976.

10. Celanese Piping Systems, "Chemtrol's Engineering Guide to Plastic Piping Systems," 1974.

11. American Concrete Pipe Association, "Concrete Pipe Design Manual, " 1974, ACPA, 1501 Wilson Boulevard, Arlington, Virginia 22209.

12. ANSI A21.50 - Thickness Design - Ductile Iron Pipe, 1976.

13. ANSI A21.4 - Cement Mortar Lining, 1974.

14. ANSI A21.11 - Rubber Gasket Joints for Cast Iron and Ductile Iron, 1972.

15. ANSI A21.5 - Polyethylene Encasement for Gray and Ductile Cast Iron Piping for Water and Other Liquids, 1975.

16. ASCE, "Earthquake Damage Evaluation and Design Considerations for Underground Structures," February 1974, (Los Angeles Section).

17. J. Katayama, K, Kubo, N. Sato, "Earthquake Damage to Water and Gas distribution systems", pp. 396-405; Proceedings of the U.S. National Conference on earthquake engineering, Earthquake Engineering Research Institute, Oakland, California 1975.

18. Breaks in Cast Iron Pipe, A paper by Mr. W.H. Smith describing causes, identification, and prevention of breaks in Cast Iron Pipe. Cast Iron Pipe Research Association, Oak Brook, Illinois.

19. United States Pipe and Foundry, "42" and "48" Ductile Iron Pipe for U.S. Pipes.

PART I - REFERENCES - Continued

20. A Guide for the Installation of Ductile Iron Pipe (CIPRA).

21. A Guide for the Installation of Gray Cast Iron Pipe (CIPRA).

22. CIPRA Concentrated Consulting Engineering Program Reference Material.

23. Procedures for the Installation of Ductile and Cast Iron Pipe.

24. White, H.L., "External Loads on Pipe with Cement Mortar," J. AWWA, June, 1952.

25. "Backfill Lessons on a 30-inch Pipeline," Eng. News-Record, March 20, 1952.

26. Sowers, G.F., "Trench Excavation and Backfill," J. AWWA, July, 1956.

27. Reitz, H.M. "Soil Mechanics and Backfill Practices," J. AWWA, December, 1956.

28. Livingston, L.E., Jr., "Loads on Ditch Conduits," Water Sewage Works, March, 1958.

29. Los Angeles Department of Water and Power, Private Communication, (1977) to Dr. Jeremy Isenberg of Weidlinger Associates.

Part II: Stress-Strain Data of Pipe Line and Joint Materials

Introduction

The several types of joints used in water pipelines differ greatly in behavior during an earth movement or settlement. For example, a steel welded joint behaves very much like the pipeline itself; and so do some of the plastic pipe joints of epoxy and other jointing materials.

In this part of the report, the behavior of cast-iron pipe-joints is summarized. Test data on the cast-iron joints is presented, and further tests considered significant for the purpose of the present study are recommended. Finally, an attempt is made to correlate the test data with the results of simple-beam model analysis, taking into account the mechanical properties of materials like cast-iron, lead or cement mortar.

Part II of this report summarizes only the behavior of lead or cement-mortar type joints in cast-iron pipes. The behavior of concrete and steel pipes will be reported in successive phases of this study.*

a. Stress-Strain Relationship for Cast-Iron

Figure 1 shows the stress-strain relationship of gray cast-iron in tension and compression. Figure 2 shows the stress-strain curve for pearlitic gray iron. For these materials both the ultimate strength and the secant elastic modulus in compression are higher than in tension (Fig. 3).

Cast-iron never exhibits a truly elastic response. At the first application of load (Figs. 4a and 4b), some plastic deformation takes place. A typical stress-strain curve for cast-iron is shown in Fig. 4a.

*An excellent report, "Welded Steel Water Pipe Manual," containing 616 references on various aspects of steel pipe behavior was made available to Weidlinger Associates by the Bethlehem Steel Company.

TABLE I : PROPERTIES OF GRAY CAST IRON

ASTM #	WEIGHT lb/in^3	E 10^6 lb/in^2	POISSON'S RATIO *	ULTIMATE TENSILE STRENGTH KSI	TENSILE YIELD STRENGTH KSI	ULTIMATE COMPRESSIVE STRENGTH KSI	ULTIMATE SHEAR STRENGTH KSI	MODULUS OF RUPTURE IN CROSS BENDING (KSI)
20	.251	14	.25	20	—	90	32	46
30	.260	15.2	.25	30	—	115	44	57
40	.260	18.3	.25	40	—	130	51	66
60	.270	19	.25	60	—	180	72	100
DUCTILE CAST IRON	.266	26	.25	50-65	32-45	200	49	62

NOTE :

* For gray cast-iron, Poisson's ratio varies between .18-.27 and falls as the stress rises. The variation of Poisson's ratio with stress levels is shown in Fig. 6 & 7.

(From: Roark, R.J.; & Young, W.C.; "Formulas for stress & strain", McGraw Hill Book Co., 1975).

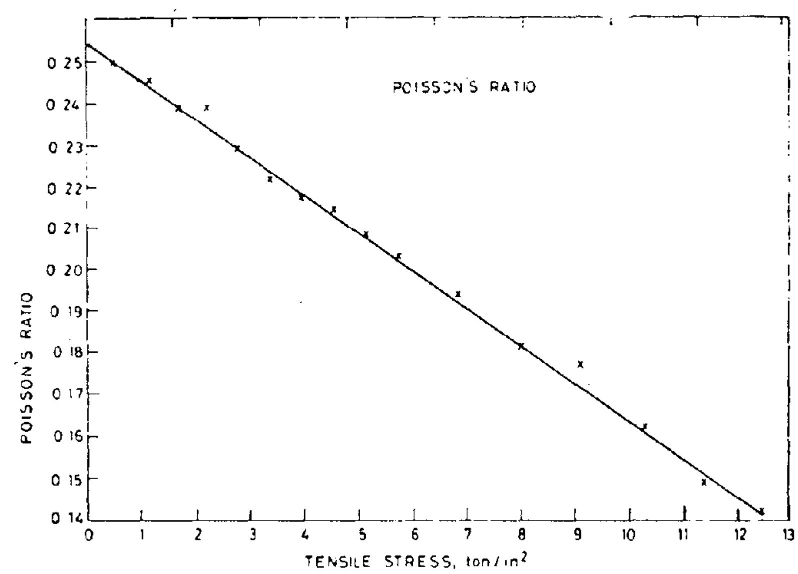


Figure 6

Variation of Poisson's ratio with Tensile Stress

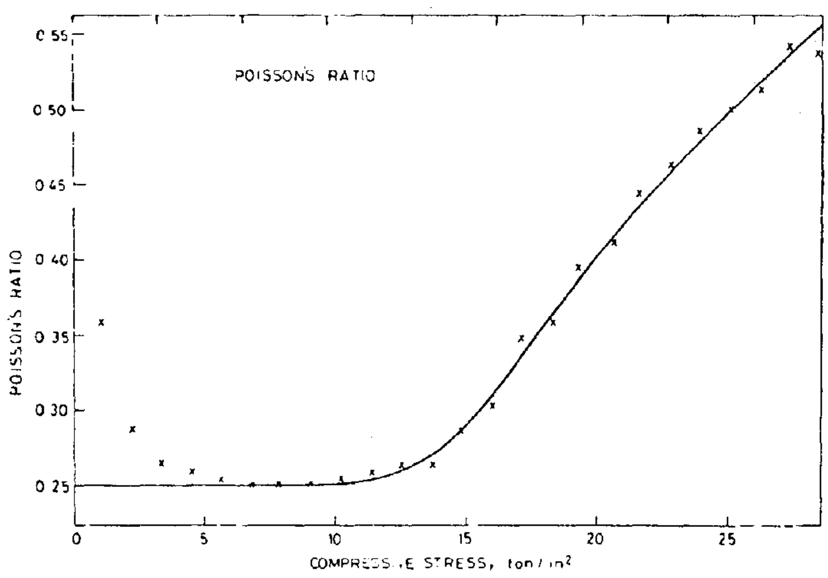


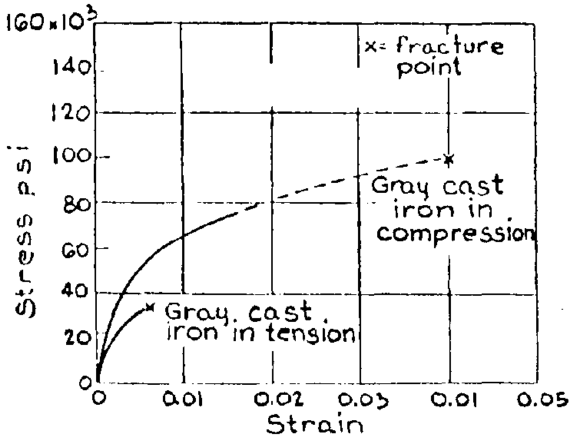
Figure 7

Variation of Poisson's ratio with Compressive Stress.

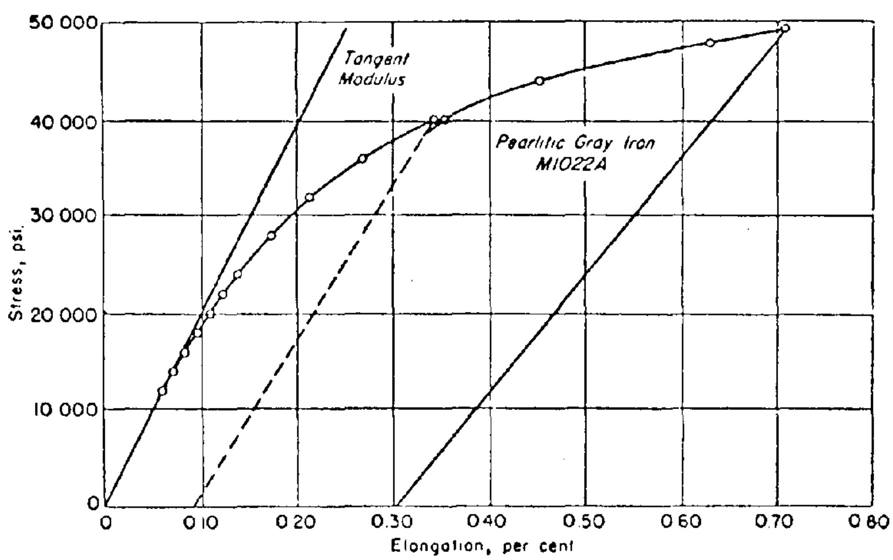
The stress-strain curves for cyclic loading of cast-iron shown in Figs. 5a, 5b and 5c show that the stress-strain curves follow different paths during loading and unloading. The major reason for this behavior is that the metal matrix is not continuous but broken up by the presence of graphite flakes which (in tension) behave as voids.

Representative structural properties of cast-iron are summarized in Table I.

In a paper presented by H.M. Hardy and T.O Kuivinen at the ASTM symposium on testing of cast-iron with SR-4 type gage (Ref. 8), the authors presented stress-strain relationships of cast-iron in tension and compression. Fig. 8 shows stress-strain curves for cast-iron beams of various shapes. Figs. 9, 10, 11 and 12 show the stress-strain distribution across the cross sections of circular, rectangular, I-section and H-section beams, respectively. It should be noted that in the I and H sections the strain distribution in the high tension zone exhibits a slight non-linearity. In all the cases shown a shift of the neutral axis takes place towards the tension side. Another conclusion of importance is illustrated by Figs. 13 and 14, which show that, within 10% accuracy, the use of a linear MC/I for the calculation of stresses in beams of cast-iron will be correct up to maximum stress of 16,000 psi. Figs. 15 and 16 show a detailed stress-strain curve for gray cast-iron (from tests by Flinn and Ely reported at ASTM-SR-4 Symposium #97, Ref. 8).



Fig·1 - Stress-strain curves for cast iron (Data for cast iron from Coffin, 1950 and Indberg and Sale, 1926.)



M 1022-A:	Total carbon, per cent	2.96
	Combined carbon, per cent	0.64
	Graphitic carbon, per cent	2.32
	Manganese, per cent	1.00
	Phosphorus, per cent	0.11
	Sulfur, per cent	0.10
	Silicon, per cent	1.49
	Brinell hardness number	207

Fig. 2—Stress-Strain Curve of a Typical Pearlitic Gray Cast Iron.

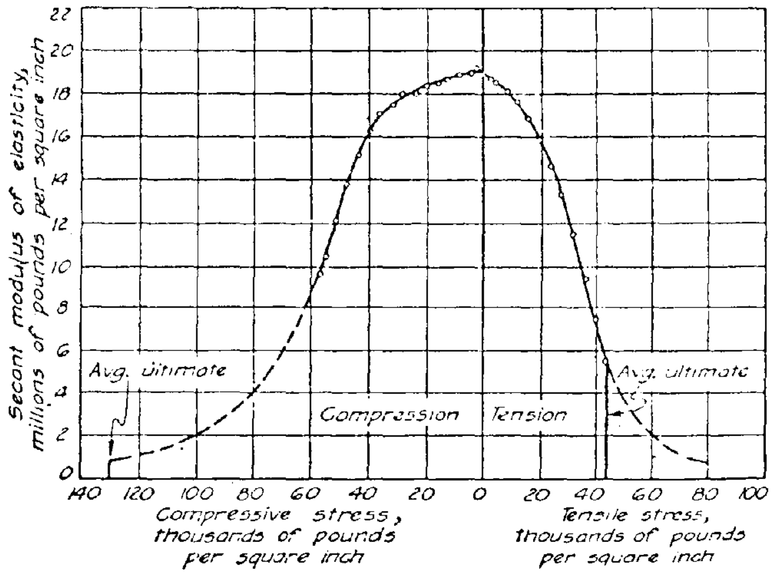


Fig. 3 —Average secant moduli of elasticity—specimens from 0.90-in plates of No. 4 iron.

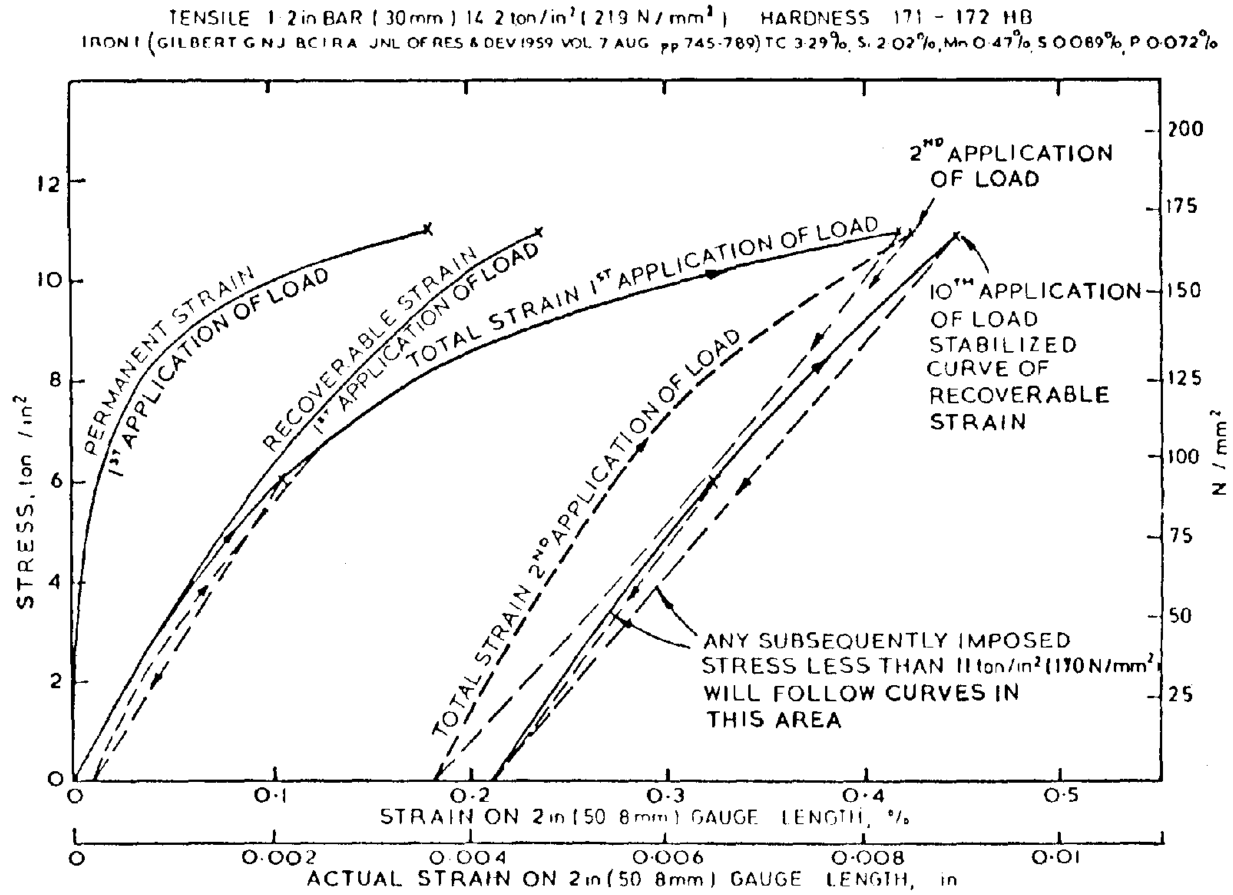


Figure 4a Typical stress/strain curves for the 1st application of stress of 11 ton/in² (170 N/mm²) and the stabilised stress/strain curve after 10 applications of a stress of 11 ton/in² (170 N/mm²) tensile

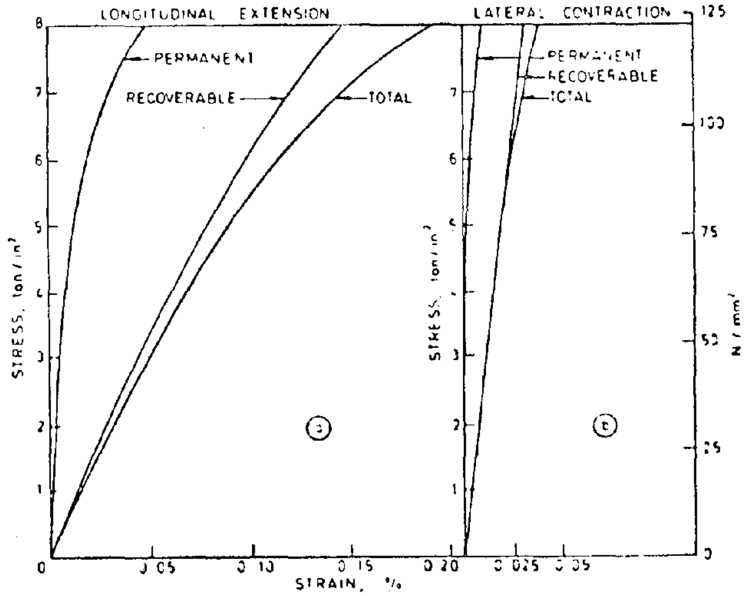


Fig. 4b: Stress - Strain curve for gray Iron.

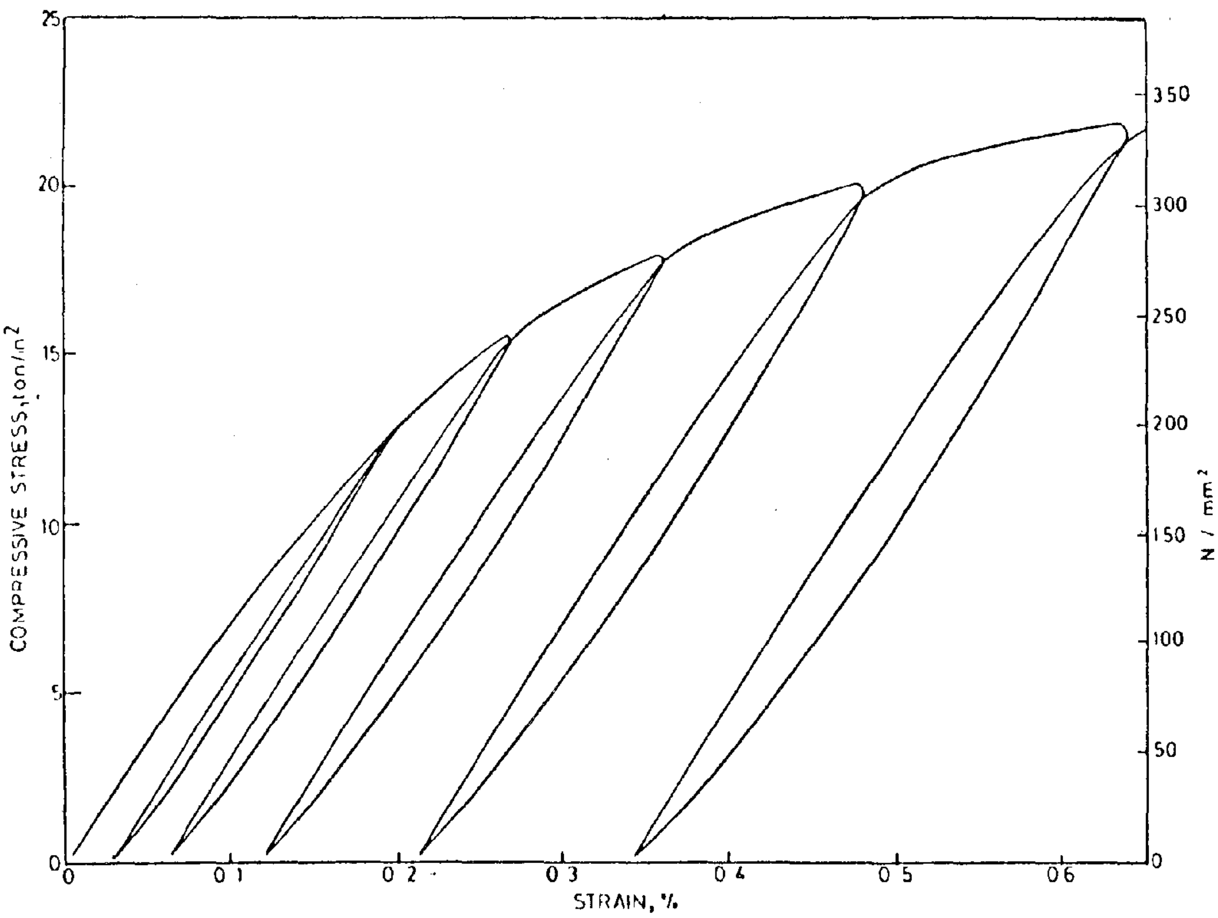


Figure 5a Compressive stress/strain curve of a flake graphite cast iron as-cast condition

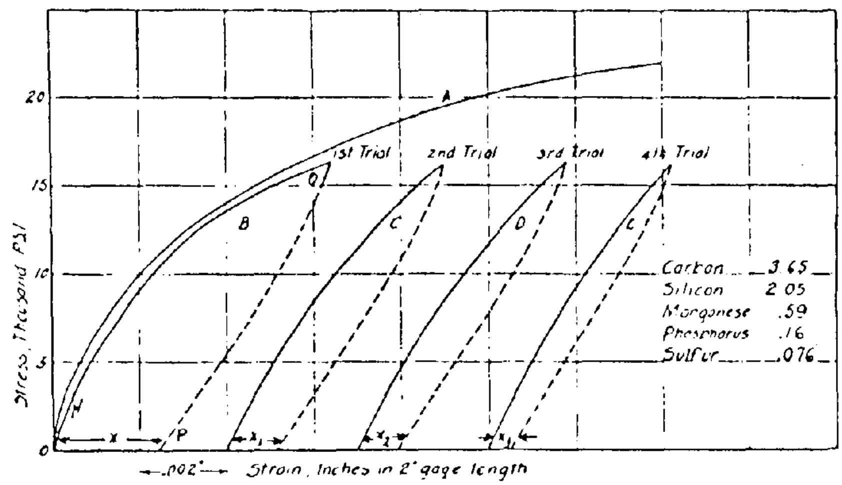


Fig. 5b - After several restressings the stress-strain curve approaches a straight line and further permanent set does not occur

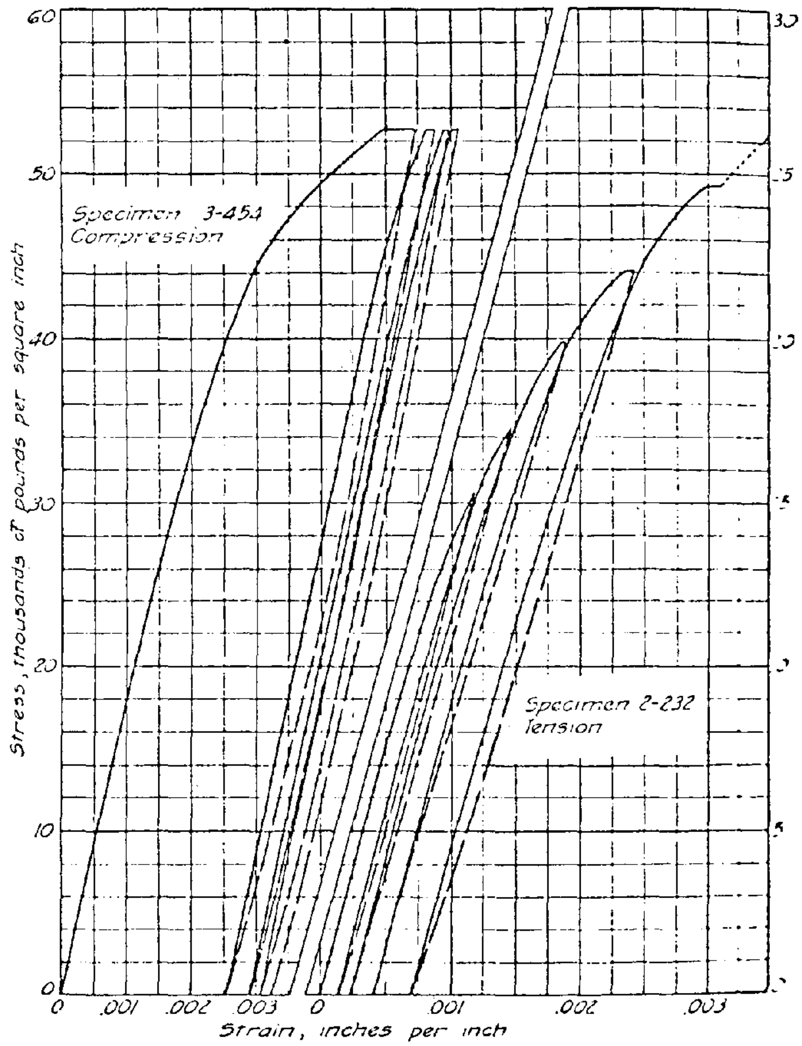


Fig. 5c—Stress-strain data for repeated loadings.

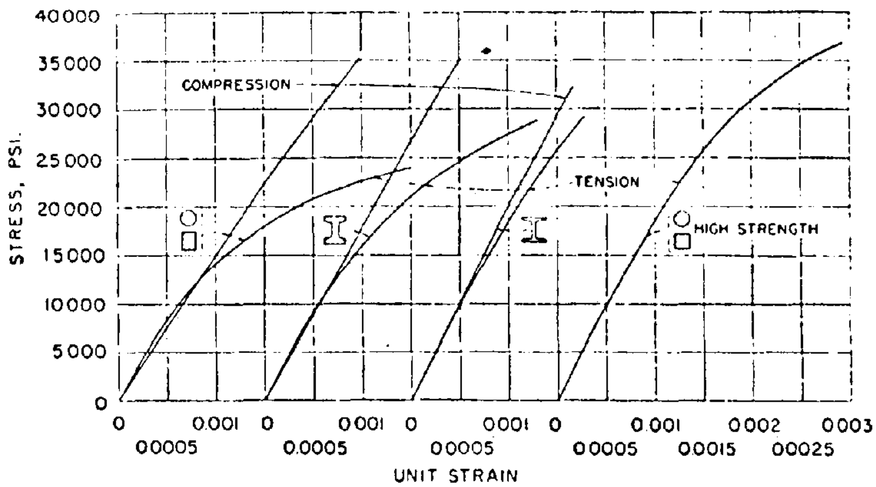


Fig. 8 STRESS-STRAIN CURVES FOR BEAM MATERIALS

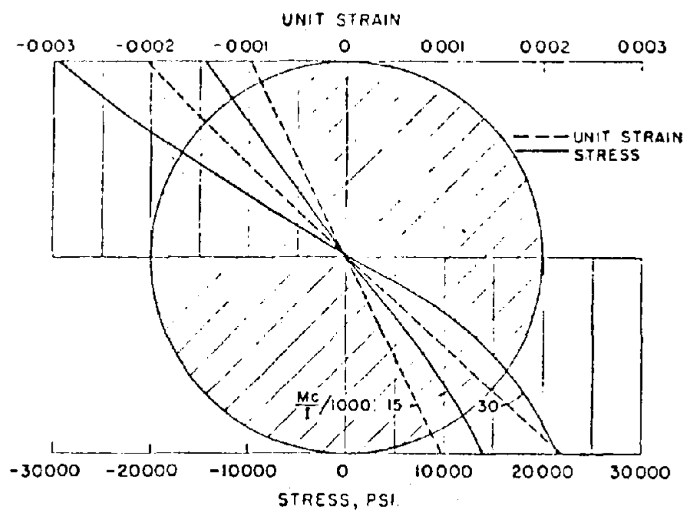


FIG. 9 —Stress-Strain Curves—Circular Beam.

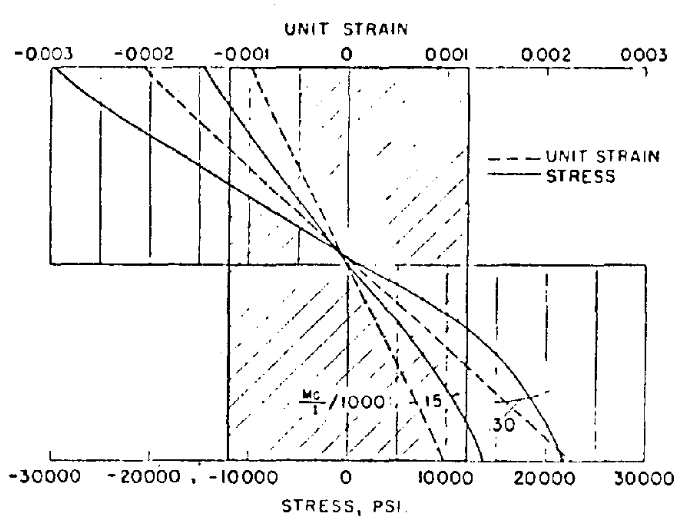


FIG. 10—Stress-Strain Curves—Rectangular Beam.

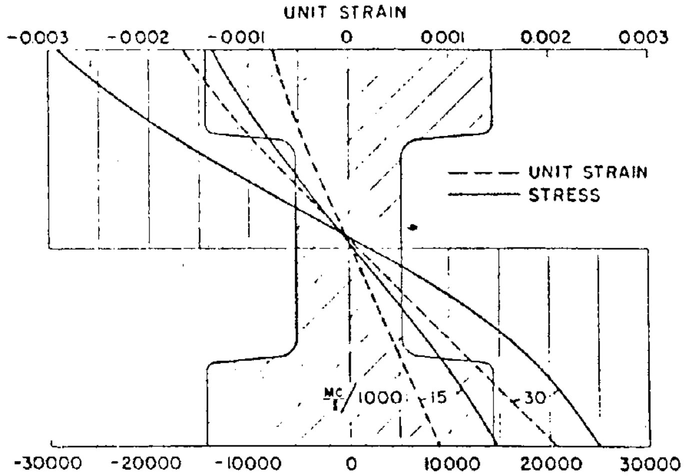


Fig. 11 —Stress-Strain Curves—I Section Beam.

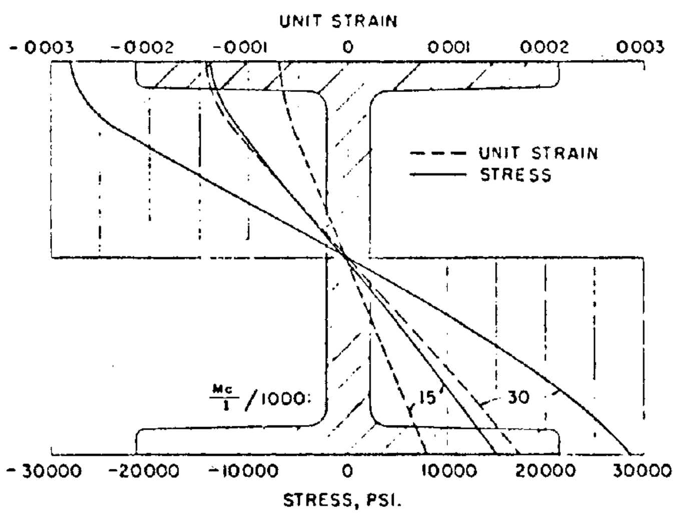


Fig. 12--Stress-Strain Curves—H Section Beam.

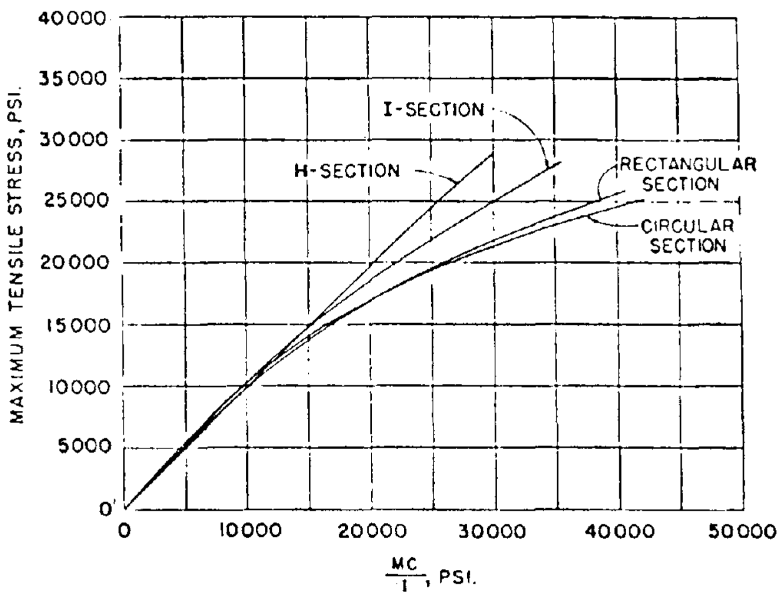


Fig. 13—Maximum Tensile Stress in Cast Iron Beams.

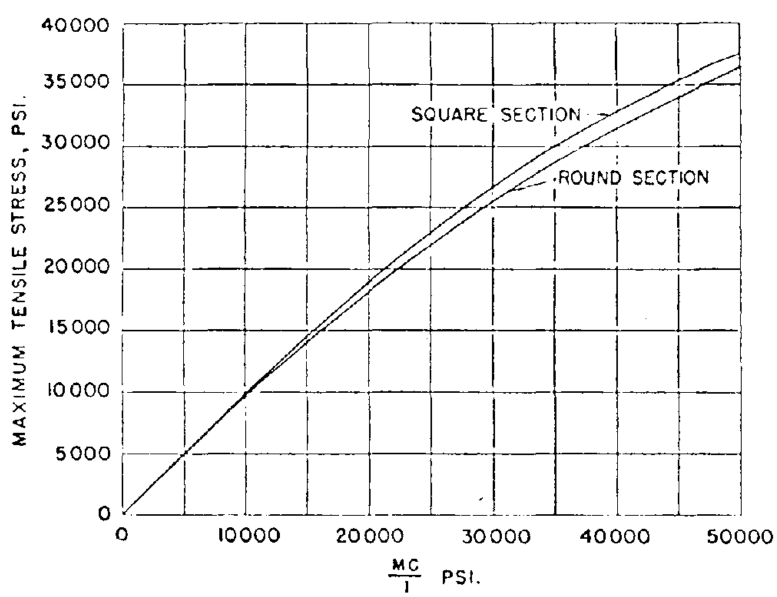


Fig. 14—Maximum Tensile Stress in High-Strength Cast Iron Beams.

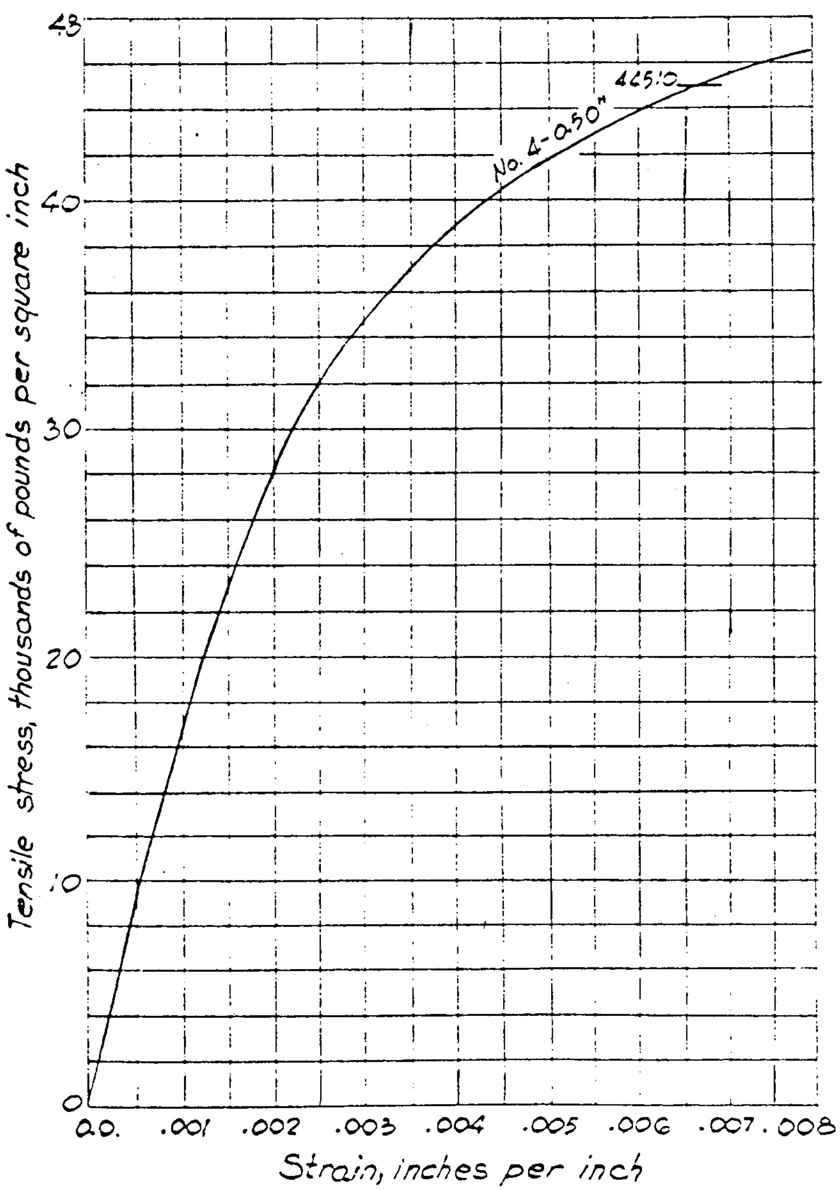


Fig. 15: Average tensile stress-strain curves.

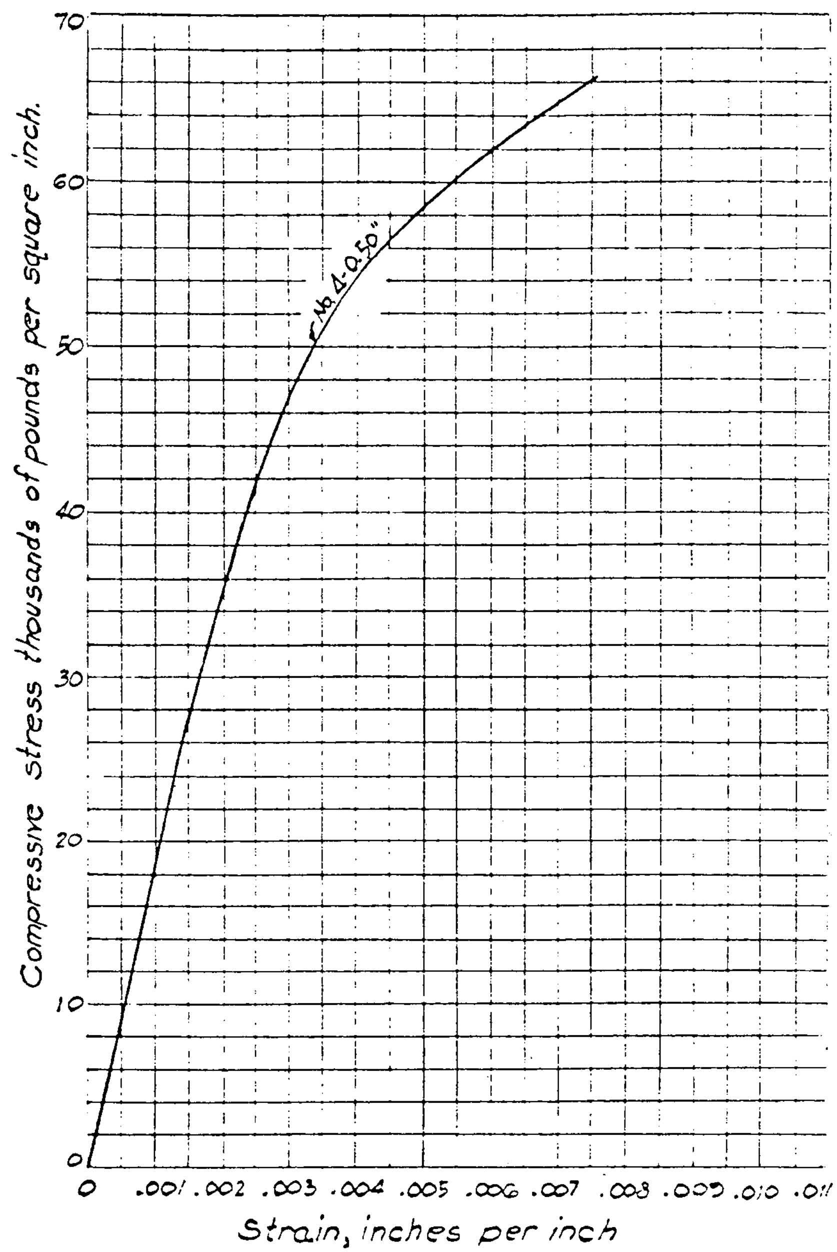


Fig. 16: Average compressive stress strain curves.

b. Failure Criteria for Cast Iron

Coffin (Ref. 1) tested, in 1950, 40 gray cast-iron tubes subjected to various ratios of combined two-dimensional stress. The results of these tests appear in Fig. 17. Coffin found that Mohr envelope criterion is not satisfactory for the fracture of gray cast iron, since in the tension-tension and tension-compression regions, it does not predict the correct fracture surface.

Table V summarizes maximum failure stresses for an 18/40 cast-iron pipe (Elastic modulus = 15 x 10^6 psi)

Table V - Failure stresses: cast iron/ductile cast iron

Type	Units	Cast Iron	Ductile Cast Iron
Ring Tension	psi	18,000	50,000
Ring Compression	psi	90,000	200,000
Ring Buckling (Euler)	psi	19,600	33,973
Bending (Rupture)*	psi	40,000	62,000
Torsion*	psi	27,000	49,000
Shear	psi	32,000	49,000

*Assuming linear behavior

c. Dynamic Properties of Cast Iron (Ref. 2).

It is found from dynamic tests that the dynamic modulus of elasticity on previously stressed cast iron bars is up to 10% higher than that obtained from static tests. For unstressed bars the dynamic modulus of elasticity is 10% lower than the static modulus.

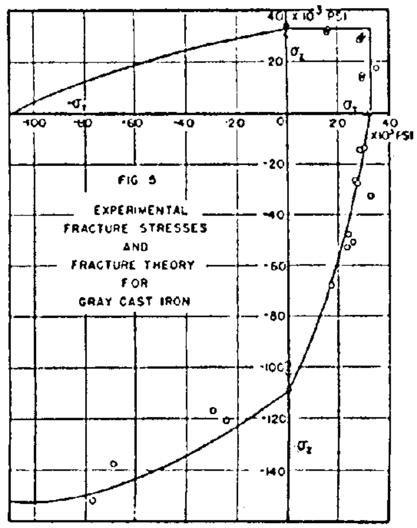


FIG. 17

Failure Criteria for Cast Iron

d. Damping in Cast Iron (Ref. 2)

The damping capacity** for grey iron is a function of the stress level and of the graphite content. For low strength iron, the damping capacity values have a range of 18-28%, for high strength grey iron the range is 3-12.5%.

e. Mechanical Properties of Lead

Many old cast-iron pipes use lead caulked joints. Since the flexibility of these kind of joints depends on the mechanical properties of lead, it must be noted that:

1) Lead has a highly non-linear stress-strain relationship with ultimate strain levels of 60-80%.
2) The behavior of lead is strain-rate dependent.
3) Lead exhibits large amounts of creep at ordinary room temperatures.

Due to the non-linear time dependent (creep) behavior of the lead, the deflection of lead-jointed pipes subjected to loads at the joints is also found to be non-linear and time dependent.

The lead or lead-wool used for caulking pipe joints must meet the requirements of the American Water Works Association's specifications AWA C600-54% Sec. 9a.5.

Lead is used as a caulking material, because:

1) It does not corrode due to varying conditions of weather, exposure to most types of soils and action of corrosive chemicals.
2) Due to the high density of lead, caulked lead joints, when properly installed, prevent leakage of water at the joint.

**The damping capacity of an oscillating material is defined as the amount of energy absorbed per oscillation expressed as a percentage of the initial energy.

Some of the basic properties of lead are listed below:

1) Cast lead weighs 707 lb/cu ft at 20°C. (68°F), its melting point is 621°F, its ultimate Tensile Strength varies from 1400 to 1700 psi.

2) The tensile strength of annealed lead, at 100°C, is 1920 psi with an ultimate elongation of 31%.

3) Common lead fails after 72 cycles, when subjected to alternate 90° reverse bends over 5" rolls at 11 cycles per minute and 200 psi tensile stress.

4) The creep characteristics of lead at room temperature are:*

Stress (psi)	creep, % per hour
200	5×10^{-5}
300	3.5×10^{-4}
400	11×10^{-4}

5) The fatigue limit of lead at 215 psi is 5×10^{7} cycles.

Commercial lead is found in almost every part of the world and, usually, contains a small amount of silver and a considerable amount of antimony. Some commercial lead contains an average of about 17% of antimony and about 2% of other metals such as arsenic and copper. (Lead with antimony and other metal impurities is sometimes called "type metal" or "hard metal.")

6) Pure commercial lead (99.9% lead) shows a tensile strength of 1900 psi and an elongation of 55% when tested at a rate of .25 in/in per minute, but, owing to the plasticity and creep characteristics of lead, these values vary greatly with changes in the rate of application of the load.

*These lead properties were obtained from Lead Industries Association, 292 Madison Avenue, New York, N.Y. 10017.

7) Other mechanical properties of lead can be summarized as follows:

compressive strength	= 2120 psi @ 32% strain
tensile strength of chill cast lead	= 1820 psi
shear strength of rolled lead	= 3000 psi
elastic modulus of rolled lead	= 2,130,000 - 2,400,000 psi
elastic modulus of annealed lead	= 2,550,000 psi
shear modulus of rigidity	= 780,000 psi
Poisson's ratio	= 0.43

Some typical stress-strain diagrams for lead with various levels of impurity are shown in Fig. 18 and tables II.*

f. Tests on Cast Iron Pipes and Joints

1. Axial and Bending Behavior (Ohio State University Tests)

Prof. Prior of Ohio State University (Ref. 3) carried out tests in 1935 to investigate the pull-out strength of bell-and-spigot cast-iron water pipes joints. The tests were carried out on pipes jointed by:

- soft lead
- lead wool
- alloy lead
- portland cement, and
- sulphur compounds.

For both the lead and sulphur compound joints, he found that the pulling force F at which incipient failure is to be expected is well represented by:

$$F = \left(\frac{3,800}{D+6} - 40\right) \frac{\pi D^2}{4} \quad \text{lbs.},$$

where D is the diameter of the pipe in inches.

*These data were obtained from Lead Industries in New York City

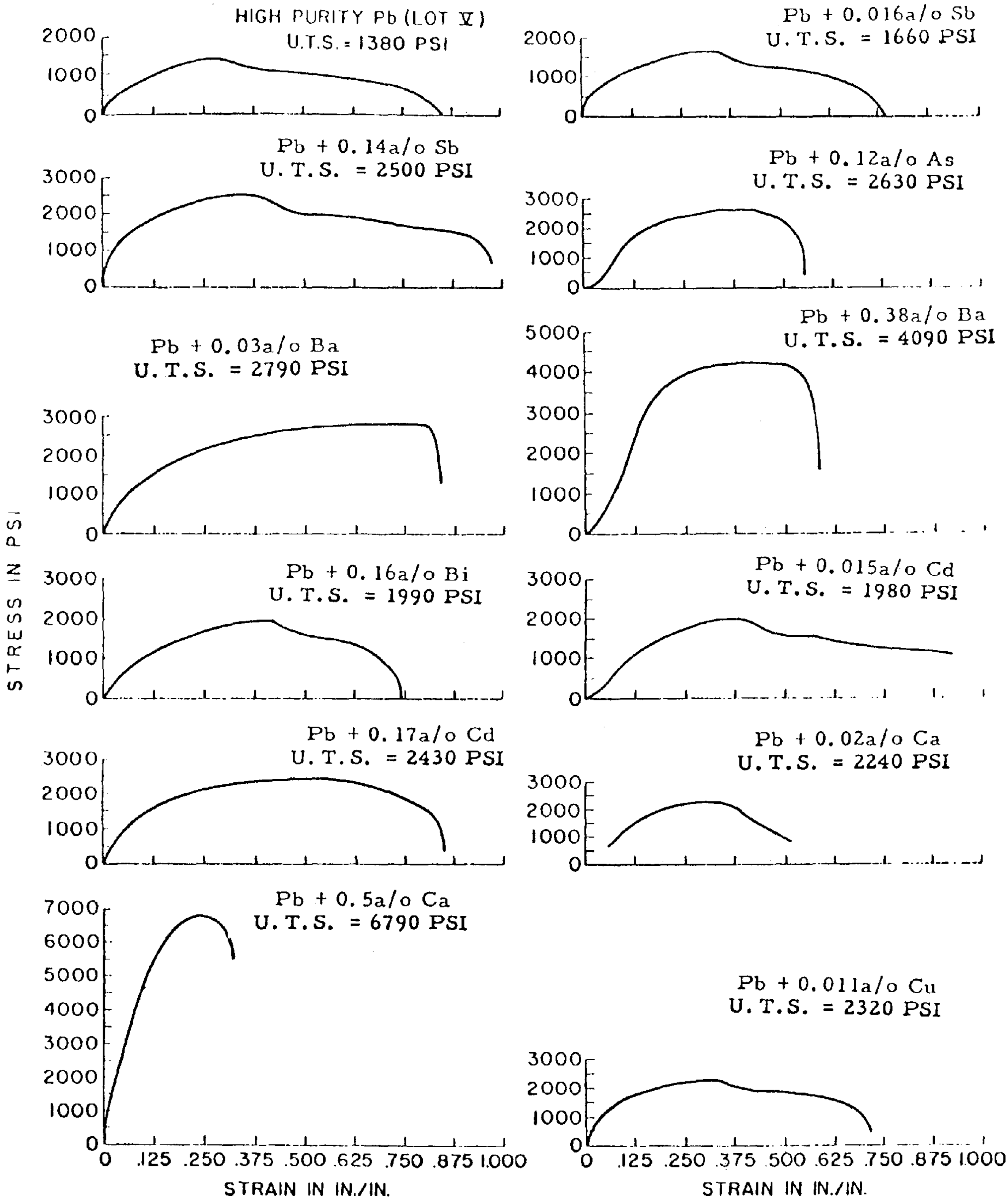


FIG. 18 - STRESS-STRAIN CURVES FOR LEAD BASE ALLOYS

TABLE II

THE CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF BINARY LEAD-BASE ALLOYS

Melt No.	Alloying Addition	Chemical Analysis w/o	Chemical Analysis a/o	Ultimate Tensile Strength, psi	Elong., % in 1 in.
-	High-purity Pb	--	--	1380	59
1	Sb	0.0095	0.016	1660	58
2		0.045	0.077	2020	52
3		0.085	0.14	2500	56
4		0.22	0.37	2590	70
5		0.84	1.4	2980	54
6	As	0.001	0.003	2040	75
7		0.008	0.02	2330	46
8		0.031	0.086	2650	33
9		0.042	0.12	2630	30
10		0.044	0.12	2540	42
11	Ba	0.002	0.003	1660	39
12		0.02	0.03	2790	52
13		0.02	0.03	2740	57
14		0.068	0.10	3500	54
15		0.25	0.38	4090	34
16	Bi	0.0012	0.0012	1880	75
17		0.0060	0.0060	1950	62
18		0.16	0.16	1990	40
19		0.97	0.96	2440	78
20		11.0	10.9	3440	50
21	Cd	0.0010	0.0018	2010	57
22		0.0080	0.015	1980	83
23		0.092	0.17	2430	66
24		0.79	1.4	3150	65
25		2.36	4.27	3470	54
26	Ca	0.001	0.005	1520	59
27		0.003	0.02	1590	73
28		0.004	0.02	2240	28
29		0.044	0.23	5330	24
30		0.09	0.5	6790	13

TABLE II (Cont.)

Melt No.	Alloying Addition	Chemical Analysis w/o	Chemical Analysis a/o	Ultimate Tensile Strength, psi	Elong., % in 1 in.
31	Cu	0.0012	0.0039	1560	80
32		0.0022	0.0072	1980	51
33		0.0035	0.011	2320	46
34		0.0060	0.020	1925	64
35		0.0087	0.028	1830	44
36		0.0004	0.01	1510	80
37		0.0007	0.02	2200	45
38		0.0011	0.033	2270	52
39		0.05	1.5	3620	50
51	Se	0.0004	0.001	1820	59
52		0.0045	0.012	2500	30
53		0.026	0.068	2290	42
54		0.33	0.86	2840	33
55	Ag	0.0010	0.0019	2380	63
56		0.010	0.019	2380	63
57		0.021	0.040	2520	54
58		0.20	0.38	2750	45
59		0.49	0.94	3400	41
60	Te	0.0005	0.0008	2220	44
61		0.0010	0.0016	2300	50
62		0.0010	0.0016	2300	44
64		0.0049	0.0080	2400	33
65	Tl	0.0008	0.0008	1925	54
66		0.010	0.010	1940	52
67		0.12	0.12	1540	73
68		0.87	0.88	2070	50
69		9.00	9.11	2420	88
70	Sn	0.0081	0.014	1420	48
71		0.153	0.267	1780	38
72		0.508	0.884	2230	71
73		1.31	2.27	2960	73
74		1.37	2.37	3510	52
75	Zn	0.00146	0.00463	1620	61
76		0.0098	0.031	1870	47
77		0.0639	0.203	1720	46
78		0.126	0.399	2020	36
79		0.448	1.41	2170	29

It is to be noted that Prof. Prior's formula is based on tests where two jointed pipes, capped at the ends, were pulled apart by increasing the internal pipe pressure. This test situation differs from actual field conditions, primarily because there are no end caps in the actual pipe and the soil around the pipe provides considerable resistance to the longitudinal elongation of the pipe.

The Prior test data for lead joints show considerable creep elongation, but are of only limited value from an earthquake point of view because of their long duration. In the case of earthquake loadings, the speed of load application does not allow the lead joints to show substantial creep.

Figs. 19a, b, c summarize typical load-deflection data obtained by Prior (1935) for pipes with diameters of 24", 36" and 60". The initial extensions of the joint are influenced by the stresses in the caulking, and since the tests were long-term duration tests, the data clearly show large creep deflections.

Professor Prior also tested in bending several 20" diameter cast-iron pipes considered as beams. Two pipes were joinee by lead and cement joints, supported at the two extreme ends, and loaded in the vicinity of the joint. In such tests Prior measured circumferential deformations, the deflections of the pipes at the joints and the joint opening at the bottom of the pipe. All these tests were simple beam tests without pressure inside the pipes.

2. Bending tests (Iowa State University)

Untrauer et. al. at Iowa State University (Ref. 4) carried out tests in 1970 to determine the effects of building movements and soil settlements on the strength requirements of cast-iron soil-pipe systems. Four inch diameter

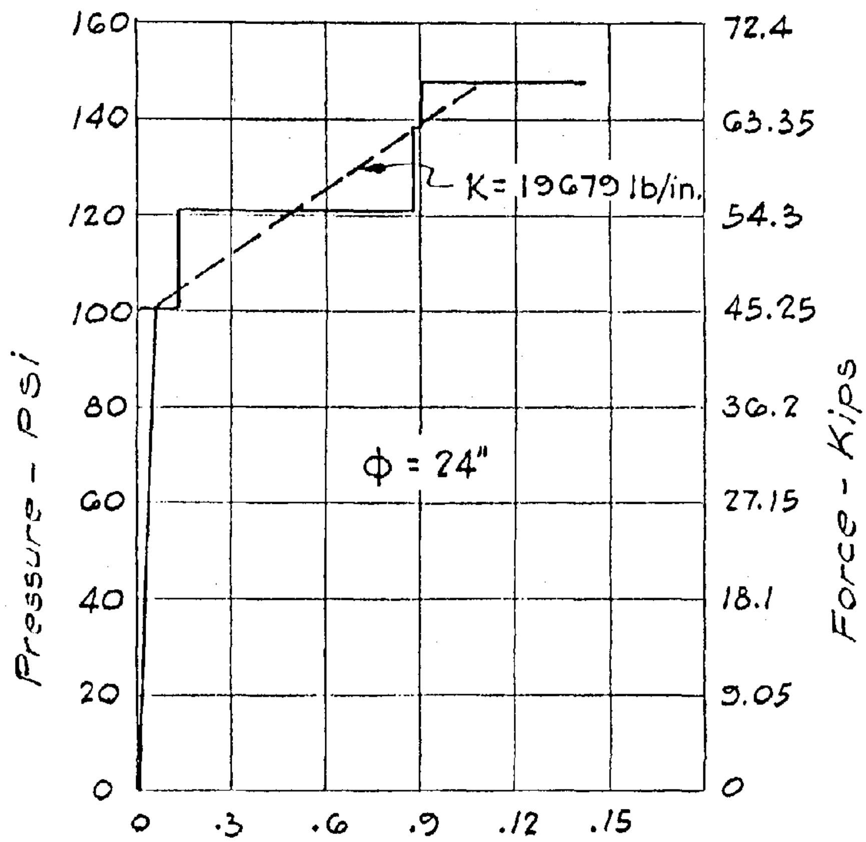


Fig. 19a : Deflection δ -inches

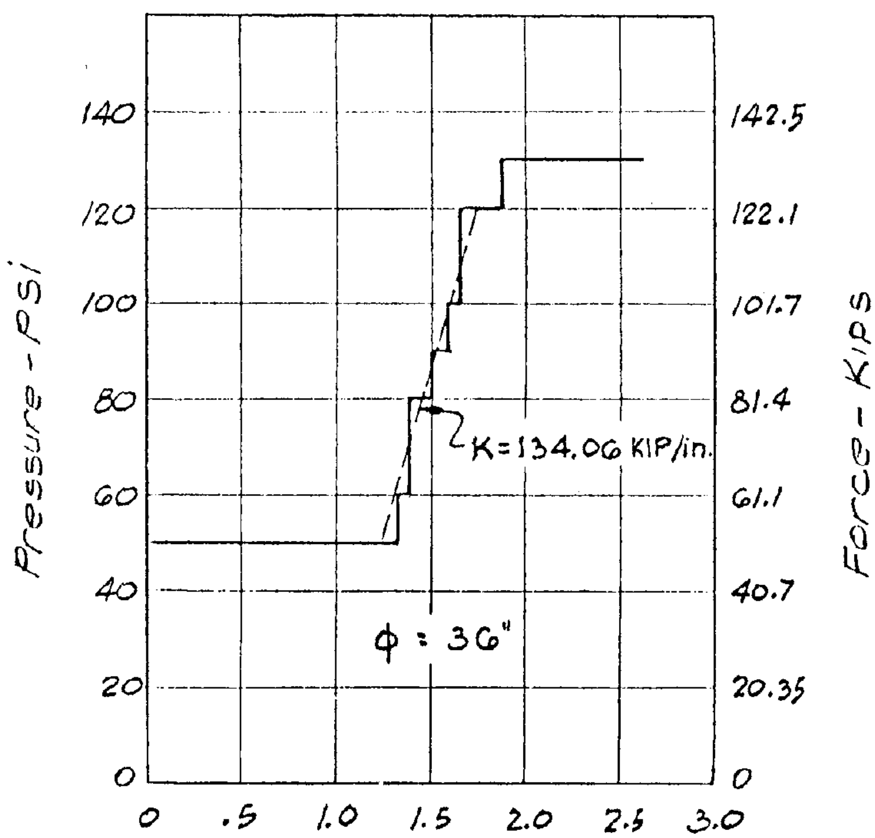


Fig. 19b: Deflection δ inches

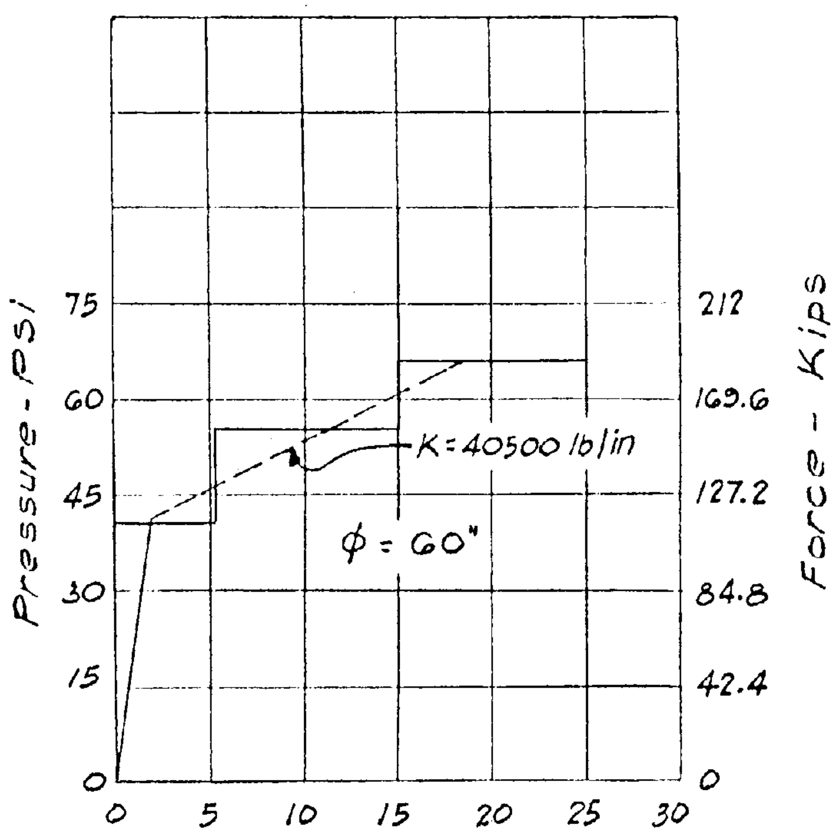


Fig.19c: Deflection δ inches

ipes were tested to study:

The behavior of lead-okum joints subjected to bending,

The ultimate strength of lead-okum joints subjected to bending,

The leakage of lead-okum joints,

The leakage of elastomeric gasket joints.

Seven two-pipe beam tests were conducted on 4 in. pipes. Two equal loads ere applied on the pipe at 24 in. spacings(12" on either side of the joint, hich is at midspan of a 60" simple support span).

The stress distribution in the spigot was found to be non-linear mainly ecause the spigot-end of the pipe bears against the hub wall of the other nd as the joint rotates. As a result, the ends of the pipes are subjected o a combination of bending moment, axial force and horizontal friction force. ecause of this nonlinear stress distribution, the highest rotational stiffness or a 4" pipe ($I = 4.78$ in^4) of cast-iron ($E = 16 \times 10^6$ psi) was found to e 200,000 in-lb./rad and only 355,000 in-lb./rad for an 8" diameter pipe. ig. 20 shows the moment-rotation test curve for 4" diameter with a lead-okum joint. Fig. 21 shows the stress distribtuion across the cross-section of the ipe. This figure shows that the rotational rigidity is not directly proportional to the moment of inertia of the section because of the high non-linearity of the stress distribution. It should be noted that the rotational rigidity on the joints depends,among other things on:

. the caulking forces

. the amount of lead in the joint

. the internal water pressure, and

. the speed at which the load is applied to the joint.

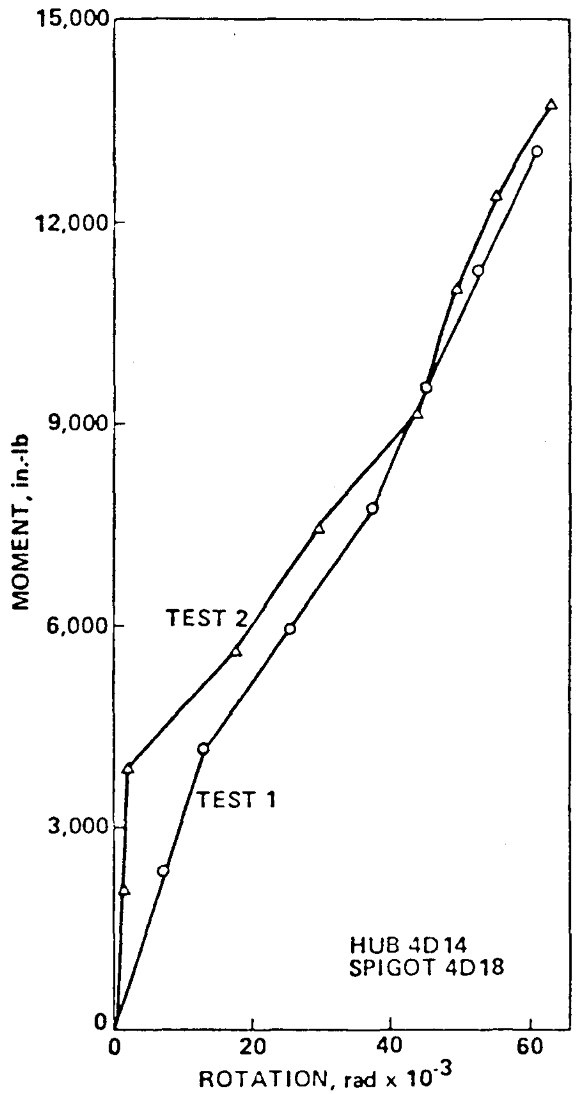


Fig. 20: Moment rotation relations for lead-oakum joints.

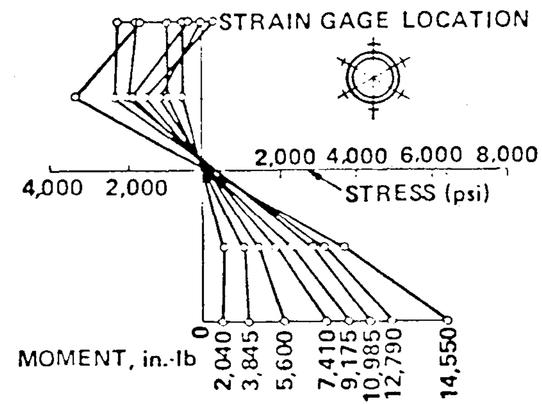


Fig. 21: Stress distribution in the spigot (4D18) of a test joint.

Table III summarizes the overall results of the tests on cast-iron soil-pipes. The table shows the average value of the test results. The testing time for ultimate strength varied from one to ten minutes. The tests have shown that the ratios between the joint rotation at ultimate load and at leakage for the 4-in. pipes were 16.20 for pressurized pipes at 5 psi pressure and 1.52 for non-pressurized pipes. For 8 in. pipes, the ratios were 2.7 for pressurized pipes and 2.04 for non pressurized pipes. The results of ultimate load tests indicate that a two-pipe system with a lead-okum joint can sustain a considerable deformation before failing.

Table III also summarizes test results for pipes joined by elastomeric gasket. All these pipes were of 4 in. diameter and the internal pressure during the beam tests was 5 psi. These tests indicate that elastomeric gasket joints can undergo considerably more rotation than lead-okum joints before leakage occurs.

The Iowa test results lead to the following conclusion:

i. Since lead-okum joints possess little rotational restraint against bending, lower stresses develop in the pipe than locally in the vicinity of a joint, under earth movement or settlement loadings.

ii. A lead-okum joint can sustain considerable rotation before structural failure occurs.

iii. A joint becomes non functional because of leakage long before it reaches ultimate joint rotation under a bending moment.

3. Summary of Test Data

For bell-&-spigot joints, the strain and rotation levels for incipient and ultimate structural damage have been summarized in Table IV from the

Table III Summary of ultimate and leakage test results[(a)].

Test	Number of tests	Load (lb)	Joint displacement (in.)	Joint moment (in.-lb)	Joint rotation (degrees)
1. Ultimate strength test for 4-in. pipe[(b)] (lead-oakum)	10	4040	3.80	36,300	14.6
2. Ultimate strength test for 8-in. pipe (lead-oakum)	1	9780	4.10	88,000	15.7
3. Leakage test for lead-oakum joint, 4-in. pipe[(c)]	9	700	0.24	6,270	0.9
4. Leakage test for lead-oakum joint, 4-in. pipe[(d)]	2	2650	2.53	23,850	9.6
5. Leakage test for lead-oakum joint, 8-in. pipe[(c)]	2	985	1.52	8,880	5.8
6. Leakage test for lead-oakum joint, 8-in. pipe[(d)]	1	3440	2.02	31,000	7.7
7. Leakage test for elastomeric gasket joint, 4-in. pipe[(c)]	6	470	2.02	4,200	7.7

[(a)] Averages of number of tests indicated.

[(b)] Out of 10 tests conducted, seven had hub failures. One broke at the barrel, one at the spigot, and one did not break.

[(c)] All values in this row are for pressurized pipes with 5 psi water pressure.

[(d)] All values in this row are for unpressurized pipes (pipes were only filled with water).

tests carried out on cast-iron at Ohio University (1935) and soil-pipes at Iowa University in 1970. The test data for cast iron pipes under pressure is quite limited and almost no data are available for buried pressurized pipes subjected to earth movement loads with adequate soil support.

Prior's (1935) tests have some useful data on joint elongation and joint rotation in bending; however, these tests are long term tests and creep deflections are included in the elongation of joints, while the bending data are exclusively on unpressurized pipes.

The Iowa 1970 report is on cast iron soil-pipes which are slightly different from water pipes because of the bead in the bulb of the pipe. Also, only average results rather than detailed test results are given in the report.

g. Correlation with experimental data

An attempt has been made to correlate the test data of Prior from Ohio State University (1935) with the simple beam model of the joint, for elongation and bending tests. No correlation was found when the initial elastic modulus of lead was used: when the initial elastic modulus was used, the calculated elongations of the joints were about 1/1000 of the observed extensions (including creep). However, for many pipe diameters (viz 36") a good correlation was found,if the secant modulus for the lead joint material was used correspondin; to the stress levels acting on the joint.

On the other hand, for the beam bending deflections, the observed tests from Ohio State University data were better matched when initial elastic modulus values were used. This was also found to be the case for the Iowa State University moment-rotation test data when adjustments were made for non-linear stress distribution across the section.

TABLE IV GRAY CAST IRON JOINT

	Joint type	Maximum Elongation (inch) $\phi = 18''$	Maximum Rotation (degree)	
			$\phi = 4''$	$\phi = 8''$
Incipient Leakage	Lead	1/2"(Ave.) at p=200psi	.9	5.8
	Gasket		77	—
Ultimate Strength	Lead	1" - 3"	14.6	15.7

p = internal water pressure.

h. Recommended Test Program

Our extensive literature review shows a basic need for tests on:

1) The behavior of buried and pressurized cast iron pipes with lead and rubber gasket joints subjected to static earth movement loads.

2) The behavior of buried and pressurized lead and rubber gasket iron pipes subjected to shaking type loads.

i. PART II - REFERENCES

1. Coffin. L.F., Jr. "Flow and Fracture of a Brittle Material;" Journal of Applied Mechanics, September, 1950, pp. 233-248.

2. H.T. Angus; "Cast Iron Physical and Engineering Properties," Butterworths, 1976.

3. Prior, J.C., "Investigation of Bell-and-Spigot Joints in Cast-iron Water Pipes," The Ohio State University - Engineering Experiment Station - Bulletin No. 87; January, 1935.

4. Untrauer, R.E., Lee, Ti-Ta, Sanders Jr., W.W., Jaward, M.H. "Design Requirement for Cast Iron Soil Pipe," Engineering Research Institute Iowa State University, Ames, Iowa, Bulletin 199, May, 1970.

5. Service Records of Existing Cast Iron Mains - Laid in the 17th, 18th and 19th Centuries.

6. Harish D. Merchant "Recent Research on Cast Iron" - 1968.

7. M.G. Spangler "Investigation of Loads on Three Cast Iron Pipe Culverts Under Rock Fills," Iowa State College, 1931.

8. Symposium on Testing of Cast Iron with SR-4 Type of Gage; ASTM, Special Technical Publication, No. 97.

9. W.J. Schlick "Strength and Elastic Properties of Cast Iron in Tension, Compression, Flexure, and Combined Tension & Flexture;" Iowa Engineering Experiment Station, June 10, 1936.

10. John W. Bolten "Gray Cast Iron - General Manufacture, Structure Mettalurgy and Engineering and Physical Properties," The Penton Publishing Co., Cleveland, Ohio, 1937.

11. Symposium on Testing of Cast Iron with SR-4 gauges - ASTM Pub. No. 97, 52nd Annual Meeting, Atlantic City, N.J., June 29, 1949.

12. "Underground Corrosion," Nat. Bur. Std. Circ. C579, Washington, D.C.

13. Schneider, W.R., "Corrosion and Cathodic Protection of Pipelines," J. AWWA, May, 1952.

14. Bill E. Foulds, "Tapping Tests on 1976 Ductile Iron Pipe," CIPRA

15. Metals Handbook, "Cast Iron."

16. J.T. Mackenzie; "A Note on the Relations Between the Proposed Standard Test Bar for Cast Iron and the Two Existing Standards."

17. A.N. Talbot and F.E. Richard "A Study of the relation between Properties of Cast-iron Pipe Tested Under Impact, Internal Pressure and Flexure and the Corresponding Properties found in Several Kinds of Test Specimens Taken from these Frames."

i. PART II - REFERENCES Continued

18. CIPRA "Ductile Iron Pipe Test Report," 1964.

Part III: Design Methods, Modeling Data and Failure Matrix

a. Water Pipe Design Methods

The thickness of the pipe is chosen to withstand several types of loads, including operating and surge pressures as well as earth loads and truck loads. Essentially, two design methods are used in establishing the water pipe thickness depending on the type of material:

1. "The Rigid Pipe Design Method" is used for pipes made of such mateials as cast-iron and concrete. In this method the load carrying capacity of the pipe for the two basic types of loads, namely, the earth and truck loads, and the internal water pressure, is determined by the use of second or third order parabola interaction curves, which give the external load vs. the internal pressure. Cast-iron pipes are designed by means of quadratic parabola-, concrete pipes by means of cubic parabola-interaction curves. Fig. 25 outlines the "Rigid pipeline design method."
2. "The Flexible Pipe Design Method" is used for pipes made of ductile cast-iron and steel pipes. The pipe is designed to withstand independently two types of loads, namely, trench loads (earth + truck), and internal pressure. The trench load, usually, is limited by pipe deformations rather than stresses. The flexible pipe design method yields a safer thickness than the rigid pipe method, because the flexibility of the pipe permits a more favorable combination of stresses under the two types of simultaneous loading, the trench load (which causes bending in the pipe) and the internal pressure (which causes hoop tension all around the ring). Figure 26 outlines the methodology of the "flexible pipe design method."

Fig. 1: **FLOW CHART**

CAST IRON PIPE DESIGN (ref. #5)

(typical "RIGID" pipe design)

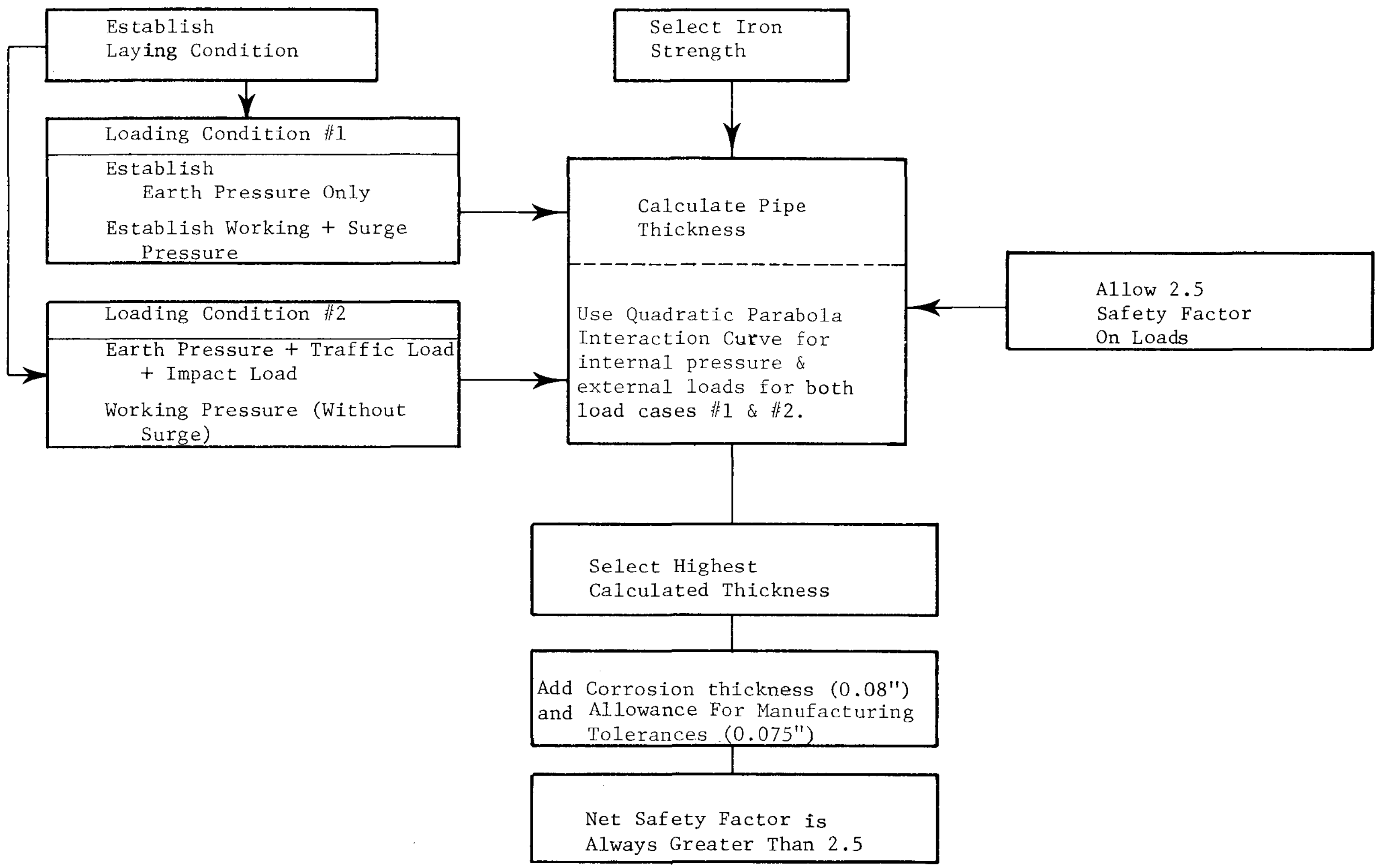
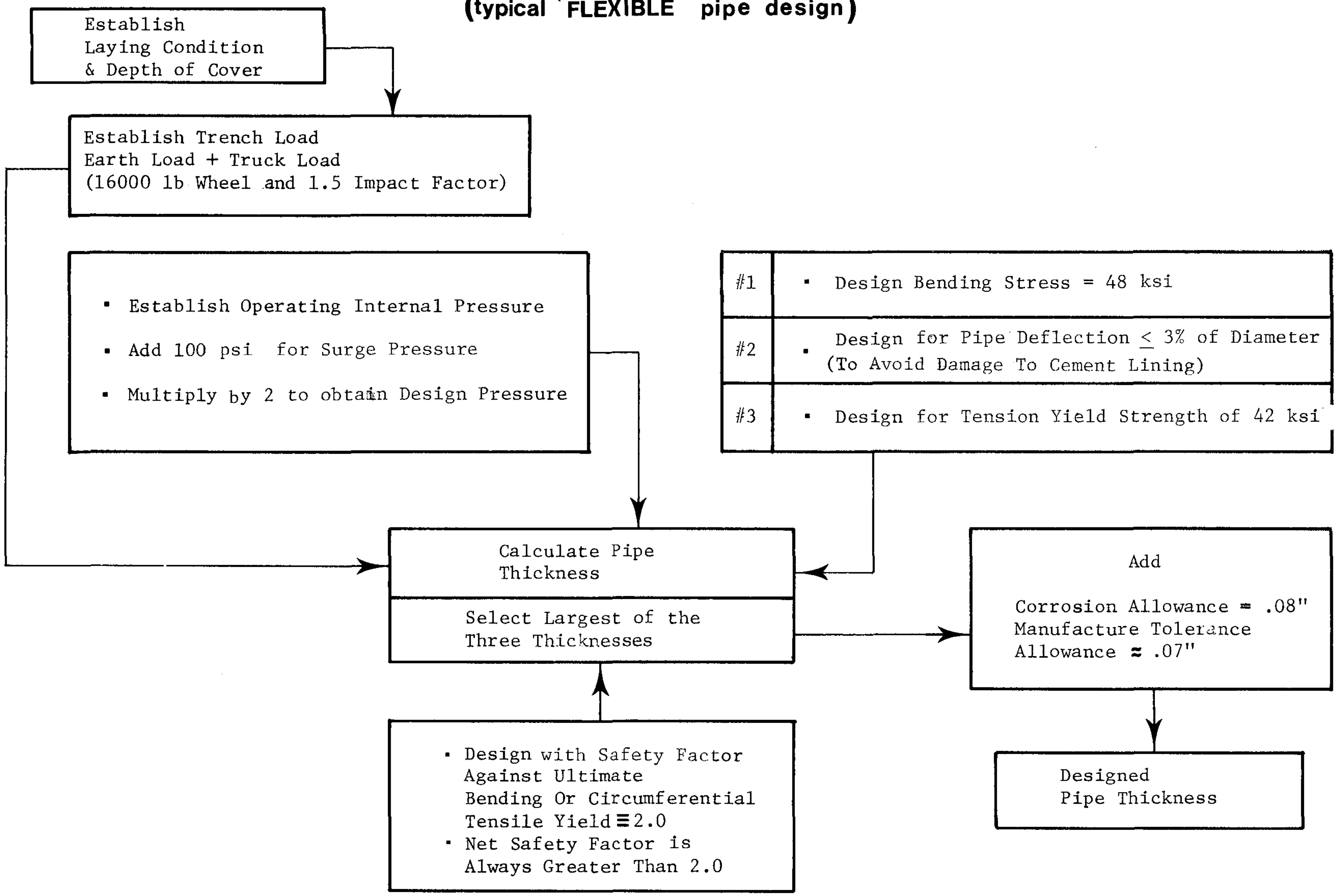


Fig. 2: **FLOW CHART**

DUCTILE IRON PIPE DESIGN (ref. 12)

(typical "FLEXIBLE" pipe design)



It must be noted that all water pipes are designed on the basis of ring stresses alone and that the design methodology of cast-iron pipes is based on ring rupture and ring bursting test data. Obviously, a cylindrical pipeline does not behave as a simple ring, but as a cylindrical shell whose stresses may be approximated by those in a beam of circular cross section elastically supported. All of the currently existing pipe design codes ignore longitudinal stresses and only consider stresses across the section of a pipe ring element. Although under normal operating conditions these beam bending stresses are likely to be marginal, in the case of an earthquake, where a dynamic strain field and also a residual displacement are likely to be imposed on the pipeline, longitudinal bending stresses in the pipes and the joints may become significant. These are never accounted for in the static design of pipeline and joints. At the present time none of the U.S. specifications or codes for pipe design have any recommendations or requirements for the earthquake design of water lifelines.

b. Major Parameters in Water Pipeline Design

Pipeline planning is usually based on present needs and on 30 years projections for population and industrial growth. The needed water pressure or the gravity gradients can be estimated on the basis of the pumping capacity and flow-head relationship of the pump, the flow-head loss characteristics of the valves and the control equipment, and the site topology.

Figure 3 shows the methodology used to determine the pipe thickness of a water pipeline made out of various materials. Cost, construction and delivery schedules, and availability of materials are some of the major parameters which control the selection of the pipe material, which is also influenced by the roughness coefficient and the strength properties of the material. Once the hydraulic roughness factor is defined for the selected pipe material, the pipe diameter can be calculated by using basic hydraulic formulas.

As indicated in the section Ib)on pipe support conditions, the soil conditions and the type of embankment are the controlling factors for the determination of the pipe laying condition. The depth of soil cover is determined by the depth of frost penetration in the area and by the magnitude of a single truck wheel load. Usually, at least 3' of soil cover are provided for buried water pipes.

Once the mechanical properties of the material of the pipe, the pipe support condition, the earth load, the truck oad, and the internal operating and surge water pressures are known, the material thickness of the pipe can be determined as shown in Figs. 1 and 2, which correspond to rigid and flexible pipe design methods,respectively.

The structural pipe thickness thus determined has to be adjusted to allow for corrosion in the case of steel or cast iron pipes and a nominal thickness has also to be added to allow for manufacturing tolerances. The nominal pipe size closest to the adjusted thickness is then selected.

In special situations, pipe design engineers consider the influence of the following additional factors in the design of the pipelines:

. temperature changes

. vacuum in the pipeline

. soil settlement

. soil liquification

. soil wash-out or erosion, and

. earthquakes

Fig. 3: **PRESSURIZED UNDERGROUND WATER PIPES**

(most important design parameters)

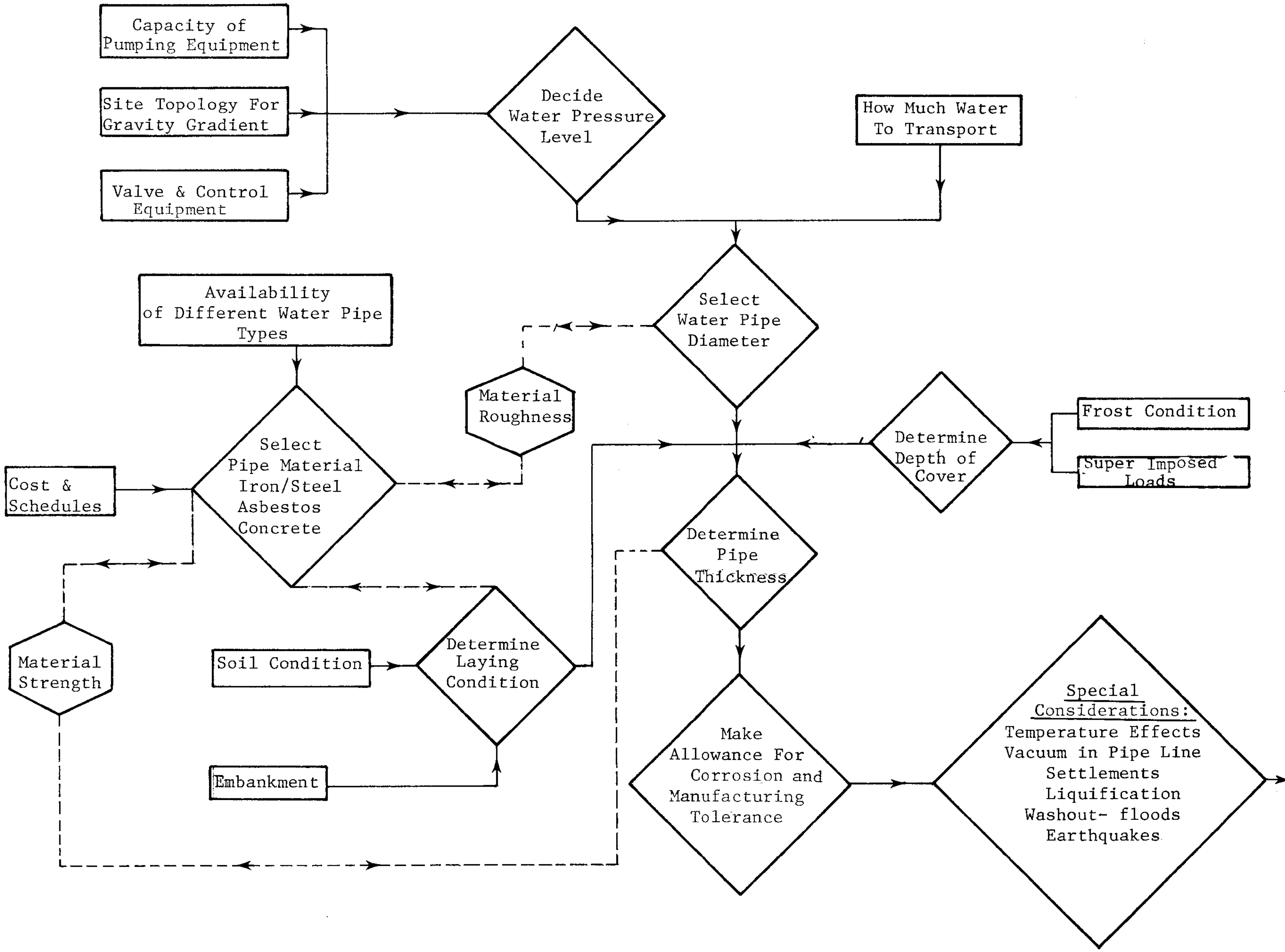


Fig. 4 obtained from The National Fire Protection Association shows the earth cover recommended to avoid freezing of the underground fire-protection water mains. In the south, the cover is about 2 1/2 - 4' and increases to 7' - 8' in the upper north.

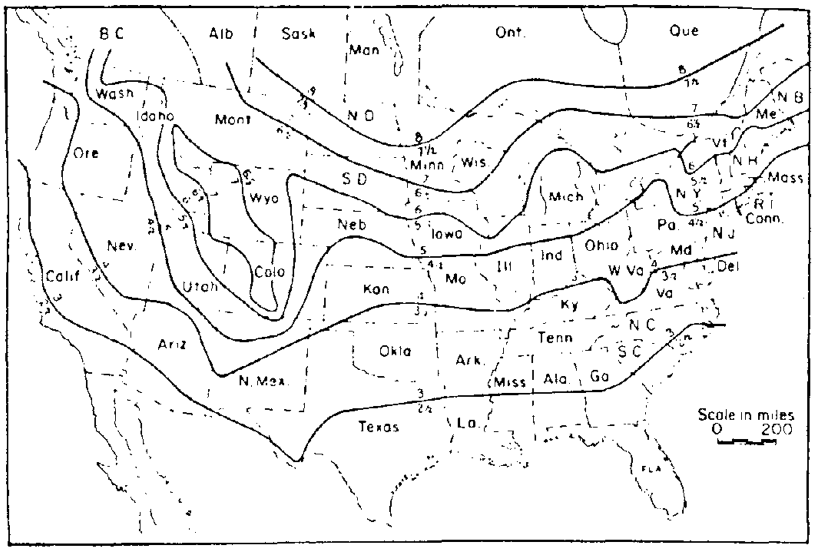


FIG. 4 Depth of earth cover recommended to avoid freezing of underground fire-protection water mains. Public water mains are usually considered safe with ½ ft less cover. (*Courtesy of the National Fire Protection Association.*)

c. Safety Factors for Pipeline Design

As shown in Figure 1, a load factor of 2.5 is used in the design of rigid pipe lines, such as pipes made of cast-iron. After corrosion, manufacturing tolerance and nominal available size thickness adjustments are made, the actual pipe thickness yields a considerable higher factor of safety against the ultimate strength of the material. Cast-iron pipes with 40,000 or 45,000 psi minimum ultimate tensile strength, usually, have a safety factor, defined as the ratio of their ultimate strength to their operating stresses (earth load + internal pressure), which lies in the range of 4 - 8. These large factors are due in part to the fact that cast-iron has a highly non-linear stress-strain curves. Such large safety factors are also indirectly reflected in the surveys, conducted by CIPRA (Cast Iron Pipe Research Association) in 18 cities of Illinois and Wisconsin, indicating that under normal operating conditions only one pipe length (usually 20 ft.) per 131 miles length of pipeline was found broken or leaking.

d. Typical Cast-Iron Pipe Modeling Data

For modeling purposes, it was deemed necessary to choose a typical type of cast-iron pipe. For feeder or distribution mains, the most common type of pipe data are as follows:

diameter = ϕ = 18"

length = L = 20'

thickness = t = .63"

elastic modulus = E = 15 x 10^6 psi

ring rupture modulus = R = 40,000 psi (bending)

laying condition 'F': bedded and tamped

depth of cover = 8'

ultimate tensile strength ≐ 18,000 psi

ultimate strain to failure = 3%

weight of pipe = 117 lb/ft (for t = 0.63")

These characteristics were used in the model analysis of the typical pipe.

e. Safety Factor Calculation Examples

This section gives a typical example of the calculation of safety factors for an 18" diameter cast-iron pipe designed according to the ANSI A 21.1 code with a load factor of 2.5. It is found that the effective safety factor for this pipe at operating condition is 5.25 and, if surge or truck loads are taken into account, it still is about 4.26.

Design Parameters = Diameter = d = 18", operating pressure = 200 psi,

cast-iron: S = 18,000 psi, R = 40,000 psi

cover = H = 5'

Type B laying condition, soil type $\phi = \theta = 10^\circ$

From soil mechanics theory or ANSI #A21.1 code:

Effective ring load = W = 1114 # / ft.

Also from code A 21.1:

t = thickness = 0.63"

$$\sigma_t = \frac{pd}{2t} = \frac{200x18}{2x.63} = 2,857 \text{ psi}$$

$$\sigma_b = \frac{Wx.0795(d+t)}{t^2} = 4,157 \text{ psi}$$

$$\sigma_{total} = 2857+4157 = 7,014 \text{ psi}$$

The reduction in R (modulus of rupture in bending) due to the internal pressure p is (from interaction curves):

$$\frac{2x18,000x.63}{18} = .92$$

Safety Factor at operating conditions = $\frac{.92x40,000}{7,014}$ = <u>5.25</u>

Case I: with 100 psi surge

$$\sigma_t = \frac{(200+100) \times 18}{2x.63} = 4,286 \text{ psi}$$

$$\sigma_b = \frac{.0795 \times 1114 \times \frac{18.63}{2}}{.63} = 4,157 \text{ psi}$$

$$\sigma_{total} = \sigma_t + \sigma_b = 4,286 + 4,157 = 8,443.$$

$$\text{Safety factor} = \frac{40,000 \times .92}{8,443} = \underline{4.36}$$

Case II: with truck load

at 5' cover, equivalent truck load $= \frac{632}{1.45} = 436$ lbs.

$$\sigma_t = \frac{200x18}{2x.63} = 2,857 \text{ psi}$$

$$\sigma_b = \frac{(1,114+436) \times 18.63x.0975}{.632} = 5,784 \text{ psi},$$

$$\sigma_{total} = 2,857 + 5,784 = 8,641 \text{ psi}$$

$$\text{Safety factor} = \frac{40,000 \times .92}{8,641} = \underline{4.26}$$

The pipes are designed for a load factor of 2.5, but due to corrosion and manufacturing tolerances the effective load factor goes up to 4.26 for 18" diameter pipes. The safety factor under operating conditions for this pipe is 5.25

f. Computer Program

A simple computer program (see Appendix A) was written to calculate the actual factor of safety under operating conditions in a cast-iron pipe designed by presently accepted methods. This factor of safety gives the margin available against the stresses produced in the pipe during earth movements.

As an input the program requires the definition of:

the pipe diameter

the internal water pressure

the depth of cover

the soil support condition (laying condition)

It is to be noted that while the maximum tensile stress of cast iron is only 18,000 psi, the 'modulus of rupture' used with linear beam theory, yields a 40,000 psi tensile stress. Thus from the load point of view, which is related to the maximum moment causing ring rupture, the apparent load factor is usually in the vicinity of 2.5; however, due to non-linear effects, the actual tensile stress is nearer to 18,000 psi than to the assumed linear stress of 40,000 psi.

g. Failure Matrix Examples

1. Introduction

The purpose of the failure matrix is to indicate for each type of pipe the ultimate strength of the pipe and of its joints under static loading conditions. The "type" of pipe is defined by its geometric and material properties, as well as by the various joint configurations and gasket shapes and materials. It is thus obvious that a complete failure matrix will contain information about a very large number of pipe types.

To exemplify the complexity of a complete failure matrix,it may be sufficient to consider cast-iron pipes only and to notice that for each of the three kinds of cast-iron used (cast-iron, malleable cast-iron and gray iron), six types of joints are generally employed:

i Push-on joint with rubber gasket (Fig.5).

ii Mechanical joint with rubber gasket (Fig.6).

iii Bell-and-spigot joint with rubber gasket (Fig.7).

iv Bell-and-spigot joint with lead or okum gasket (Fig.8).

v Flanged joints (bolted) (Fig.9).

vi Welded joints (Fig.10)

For each one of these joint-pipe combinations the codes give detailed specifications and practice manuals installation instructions. On the other hand, the amount of test data significant to seismic design is extremely limited both in the static and the dynamic range. It is one of the main purposes of the following examples to indicate what information is available on a particular type of cast-iron pipe with mechanical joints using rubber gasket and to illustrate the needs for a series of dynamic tests,that will be detailed in a subsequent report.

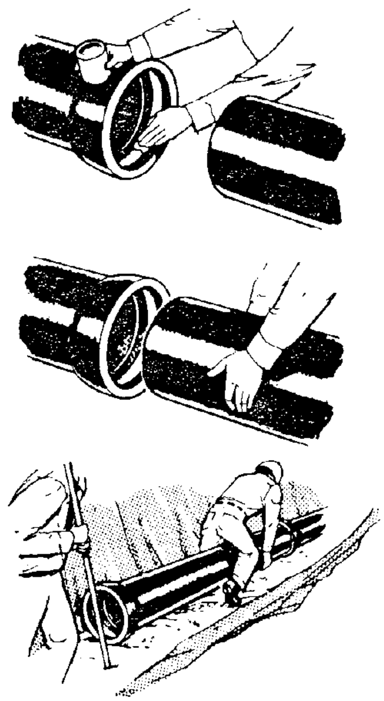


Fig. 5

Push - on joint with rubber gasket

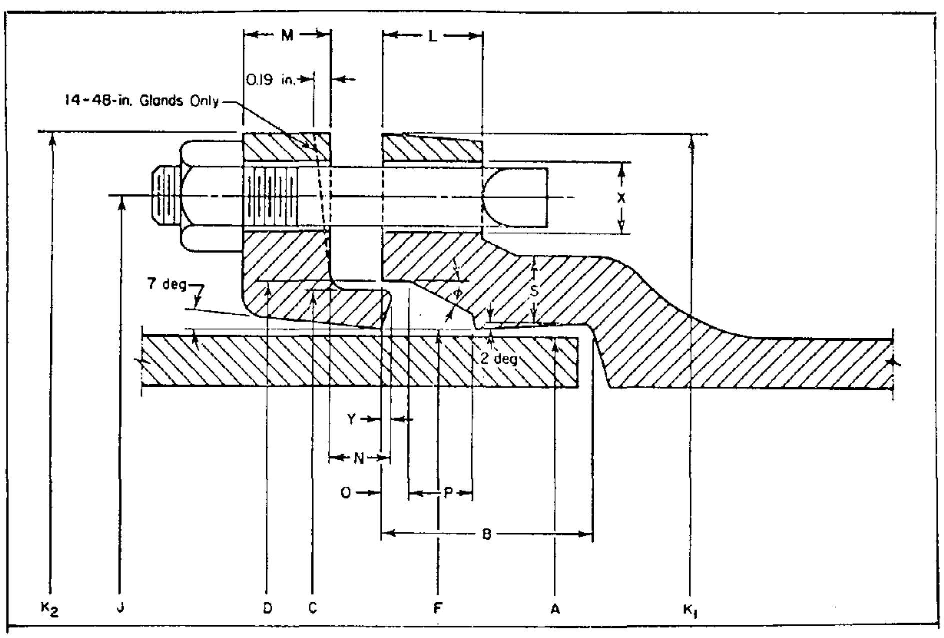


Fig. 6

Mechanical joint with rubber gasket

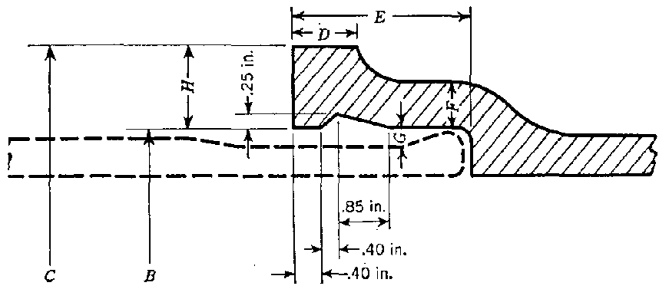


Fig. 7

Bell-and-spigot joint with rubber gasket

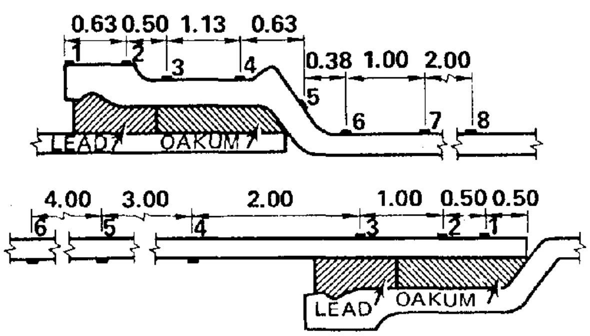


Fig. 8

Bell-and-spigot joint with lead or okum gasket

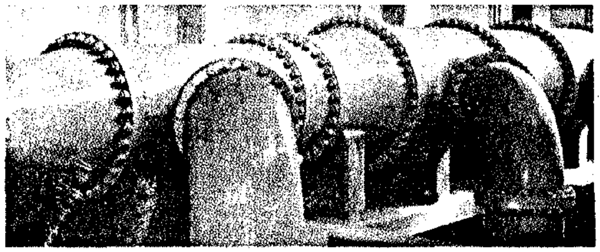


Fig. 9

Flanged joints (Bolted)

Fig. 10

Welded joints

2. Pipe failure data

The pipe of the present example is that defined in Sect. III d - "Typical cast-iron Pipe Modeling Data." The mechanical joint with rubber gasket is defined in ANSI A21.11 - 1972 Fig. 11.1 (Fig.6) with mechanical joints dimensions specified in Table 11.1, (Table I) here reproduced, and mechanical joint gasket dimensions specified in Table 11.2 (Table II) and Fig. 11.2 (Fig. 11), here reproduced.

Table III gives the ultimate stresses for the pipe itself under the indicated static conditions.

Table III

Loading condition	Ultimate stress (psi)
Axial tension	18,000
Axial compression	90,000
Bending Rupture	40,000
Torsion	27,000
Shear	32,000
Buckling	
local torsional	68,000 - 105,000
Euler	104,093
Internal pressure	18,000
Ring bending	40,000
Ring buckling (Euler)	19,600

The main characteristics for pipe failure are the ultimate tension force P_u and the ultimate bending moment M_u:

TABLE I

Mechanical-Joint Dimensions—in.

Size	*A* Plain End	*B*	*C*	*D*	*F*	*Φ*	*X*	*J*	*K₁* Centrifugal Pipe	*K₁* Pit Cast Pipe and Fittings	*K₂*	*L**	*M*	*N*	*O*	*P*	*S* Centrifugal Pipe	*S* Pit Cast Pipe and Fittings	*Y*	Bolts No.	Bolts Size	Bolts Length
2	±0.05 2.50	2.50	±0.05 3.39	±0.05 3.50	±0.05 2.61	28°	+0.06−0.0 ¾	±0.05 4.75	−0.05 6.00	−0.10 6.25	−0.10 6.25	−0.05 0.56	−0.05 0.62	0.50	0.31	0.63	0.37	−0.07 0.44	0.08	2	⅝	2½
2¼	±0.05 2.75	2.50	±0.05 3.64	±0.05 3.75	±0.05 2.86	28°	+0.06−0.0 ¾	±0.05 5.00	−0.05 6.25	−0.10 6.50	−0.10 6.50	−0.05 0.56	−0.05 0.62	0.50	0.31	0.63	0.37	−0.07 0.44	0.08	2	⅝	2½
3	±0.06 3.96	2.50	±0.04 4.84	+0.06−0.04 4.94	+0.07−0.03 4.06	28°	+0.06−0.0 ¾	±0.06 6.19	−0.06 7.62	−0.12 7.69	−0.12 7.69	−0.06 0.94	−0.06 0.62	0.75	0.31	0.63	0.47	−0.10 0.52	0.12	4	⅝	3
4	±0.06 4.80	2.50	±0.04 5.92	+0.06−0.04 6.02	+0.07−0.03 4.90	28°	+0.06−0.0 ⅞	±0.06 7.50	−0.06 9.06	−0.12 9.12	−0.12 9.12	−0.06 1.00	−0.06 0.75	0.75	0.31	0.75	0.55	−0.10 0.65	0.12	4	¾	3½
6	±0.06 6.90	2.50	±0.04 8.02	+0.06−0.04 8.12	+0.07−0.03 7.00	28°	+0.06−0.0 ⅞	±0.06 9.50	−0.06 11.06	−0.12 11.12	−0.12 11.12	−0.06 1.06	−0.06 0.88	0.75	0.31	0.75	0.60	−0.10 0.70	0.12	6	¾	3½
8	±0.06 9.05	2.50	±0.04 10.17	+0.06−0.04 10.27	+0.07−0.03 9.15	28°	+0.06−0.0 ⅞	±0.06 11.75	−0.06 13.31	−0.12 13.37	−0.12 13.37	−0.08 1.12	−0.08 1.00	0.75	0.31	0.75	0.66	−0.12 0.75	0.12	6	¾	4
10	±0.06 11.10	2.50	+0.06−0.04 12.22	+0.06−0.04 12.34	+0.07−0.03 11.20	28°	+0.06−0.0 ⅞	±0.06 14.00	−0.06 15.62	−0.12 15.69	−0.12 15.62	−0.08 1.19	−0.08 1.00	0.75	0.31	0.75	0.72	−0.12 0.80	0.12	8	¾	4
12	±0.06 13.20	2.50	+0.06−0.04 14.32	+0.06−0.04 14.44	+0.07−0.03 13.30	28°	+0.06−0.0 ⅞	±0.06 16.25	−0.06 17.88	−0.12 17.94	−0.12 17.88	−0.08 1.25	−0.08 1.00	0.75	0.31	0.75	0.79	−0.12 0.85	0.12	8	¾	4
14	+0.05−0.08 15.30	3.50	+0.07−0.05 16.40	+0.07−0.05 16.54	+0.06−0.07 15.44	28°	+0.06−0.0 ⅞	±0.06 18.75	−0.08 20.25	−0.12 20.31	−0.12 20.25	−0.12 1.31	−0.12 1.25	0.75	0.31	0.75	0.85	−0.12 0.89	0.12	10	¾	4½
16	+0.05−0.08 17.40	3.50	+0.07−0.05 18.50	+0.07−0.05 18.64	+0.06 0.07 17.54	28°	+0.06−0.0 ⅞	±0.06 21.00	−0.08 22.50	−0.12 22.56	−0.12 22.50	−0.12 1.38	−0.12 1.31	0.75	0.31	0.75	0.91	−0.12 0.97	0.12	12	¾	4½
18	+0.05−0.08 19.50	3.50	+0.07−0.05 20.60	+0.07−0.05 20.74	+0.06−0.07 19.64	28°	+0.06−0.0 ⅞	±0.06 23.25	−0.08 24.75	−0.15 24.83	−0.15 24.75	−0.12 1.44	−0.12 1.38	0.75	0.31	0.75	0.97	−0.15 1.05	0.12	12	¾	4½
20	+0.05−0.08 21.60	3.50	+0.07−0.05 22.70	+0.07−0.05 22.84	+0.06−0.07 21.74	28°	+0.06−0.0 ⅞	±0.06 25.50	−0.08 27.00	−0.15 27.08	−0.15 27.00	−0.12 1.50	−0.12 1.44	0.75	0.31	0.75	1.03	−0.15 1.12	0.12	14	¾	4½
24	+0.05−0.08 25.80	3.50	+0.07−0.05 26.90	+0.07−0.05 27.04	+0.06−0.07 25.94	28°	+0.06−0.0 ⅞	±0.06 30.00	−0.08 31.50	−0.15 31.58	−0.15 31.50	−0.12 1.62	−0.12 1.56	0.75	0.31	0.75	1.08	−0.15 1.22	0.12	16	¾	5
30	+0.08−0.06 32.00	4.00	+0.08−0.06 33.29	+0.08−0.06 33.46	+0.08−0.06 32.17	20°	+0.06−0.0 1⅛	±0.06 36.88	−0.12 39.12	−0.18 39.12	−0.18 39.12	−0.12 1.81	−0.12 2.00	0.75	0.38	1.00	1.20	−0.15 1.50	0.12	20	1	6
36	+0.08−0.06 38.30	4.00	+0.08−0.06 39.59	+0.08−0.06 39.76	+0.08−0.06 38.47	20°	+0.06−0.0 1⅛	±0.06 43.75	−0.12 46.00	−0.18 46.00	−0.18 46.00	−0.12 2.00	−0.12 2.00	0.75	0.38	1.00	1.35	−0.15 1.80	0.12	24	1	6
42	+0.08−0.06 44.50	4.00	+0.08−0.06 45.79	+0.08−0.06 45.96	+0.08−0.06 44.67	20°	+0.06−0.0 1⅜	±0.06 50.62	−0.12 53.12	−0.18 53.12	−0.18 53.12	−0.12 2.00	−0.12 2.00	0.75	0.38	1.00	1.48	−0.15 1.95	0.12	28	1¼	6
48	+0.08−0.06 50.80	4.00	+0.08−0.06 52.09	+0.08−0.06 52.26	+0.08−0.06 50.97	20°	+0.06−0.0 1⅜	±0.06 57.50	−0.12 60[illegible]	−0.18 60.00	−0.18 60.00	−0.12 2.00	−0.12 2.00	0.75	0.38	1.00	1.61	−0.15 2.20	0.12	32	1¼	6

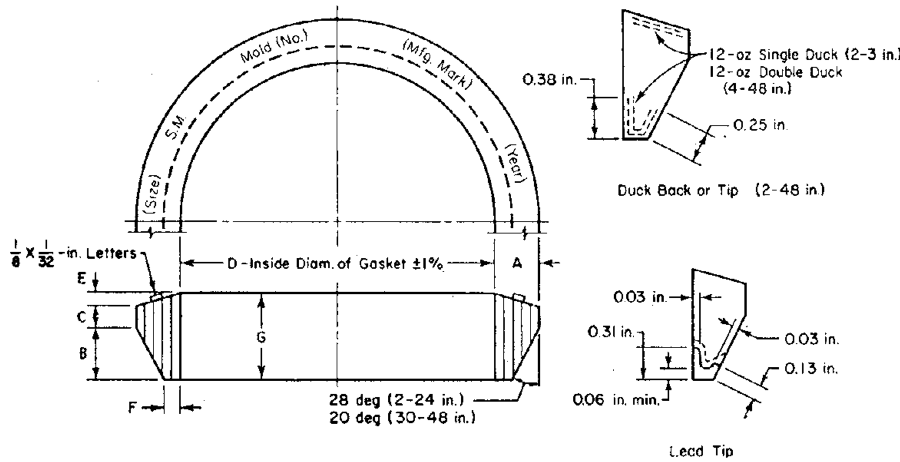


Fig. 11

Mechanical - joint gasket, 2-48 in (see table II and notes)

Notes

1. Tipped or backed gaskets may be made in the same mold as plain rubber gaskets, but the inside diameter of such reinforced portions shall not exceed the "pipe OD."
2. The duck for tips and backs shall be frictioned before molding.

TABLE II.

2-48-in. Mechanical-Joint Gasket Dimensions—in.

Pipe Size	Pipe OD	Dimensions of Plain Rubber Gaskets						
		A ±0.01 in.	*B*	*C*	*D* +1 per cent −1 per cent	*E*	*F* ±0.01 in.	*G* ±0.02 in.
2	2.50	0.48	0.62	0.31	2.48	0.12	0.15	1.05
2¼	2.75	0.48	0.62	0.31	2.72	0.12	0.15	1.05
3	3.96	0.48	0.62	0.31	3.86	0.12	0.15	1.05
4	4.80	0.62	0.75	0.31	4.68	0.16	0.22	1.22
6	6.90	0.62	0.75	0.31	6.73	0.16	0.22	1.22
8	9.05	0.62	0.75	0.31	8.85	0.16	0.22	1.22
10	11.10	0.62	0.75	0.31	10.87	0.16	0.22	1.22
12	13.20	0.62	0.75	0.31	12.95	0.16	0.22	1.22
14	15.30	0.62	0.75	0.31	14.99	0.16	0.22	1.22
16	17.40	0.62	0.75	0.31	17.07	0.16	0.22	1.22
18	19.50	0.62	0.75	0.31	19.13	0.16	0.22	1.22
20	21.60	0.62	0.75	0.31	21.20	0.16	0.22	1.22
24	25.80	0.62	0.75	0.31	25.34	0.16	0.22	1.22
30	32.00	0.73	1.00	0.38	31.47	0.16	0.37	1.54
36	38.30	0.73	1.00	0.38	37.67	0.16	0.37	1.54
42	44.50	0.73	1.00	0.38	43.78	0.16	0.37	1.54
48	50.80	0.73	1.00	0.38	49.98	0.16	0.37	1.54

$$P_{u,p} = 18,000\ [\pi(19.50 - .63)] \times .63 = 672,256 \text{ lbs.}$$

$$M_{u,p} = RS_x = R\frac{\pi}{4}D^2 t = 40,000 \times \frac{\pi}{4}(19.50 - .63)^2 \times .63 = 7,047,500 \text{ lb-in.}$$

It is confirmed by practical observations that other modes of failure seldom occur (additional verbal confirmation from Dr. S. Takada), although some compression failures have occurred.

3. Joint failure data

i. Bolt failure

From Table XI, 12 bolts of 3/4 in. diameters (area = .3345 in^2), must be used with a minimum yield strength of 45,000 psi. The ultimate tensile force P_u and ultimate bending moment M_u developed by the bolts is:

$$P_{u,b} = 12 \times .3345 \times 45,000 = 180,630 \text{ lbs.}$$

$$M_{u,b} = .3345 \times 45,000 \times \left(\frac{19.50 - .63}{2}\right)^2 [2 + 4 \times .866^2 + 4 \times .5^2] = 6,834,000 \text{ lbs. in.}$$

For a working stress of 0.6 x 45,000 = 27,000 psi, the allowable tensile force developed by the bolts is:

$$P_{a,b} = 180,630 \times 27,000/_{45,000} = 108,378 \text{ lbs.}$$

iii. Ultimate gasket friction

From Table XII the average compressed area of the rubber gasket is:

$$A_c = \left[\frac{.62+.22}{2}\right] \pi(19.5 + 0.42) = 26.28 \text{ in}^2$$

The corresponding axial compressive stress due to the allowable bolt axial tension is:

$\sigma_{c,ax} = 108,378/26.28 = 4,124$ psi

Assuming all lateral expansion to be prevented in the radial and circumferential directions and with a Poisson's ratio $\nu = 0.4$, the total stress in the radial direction developed by the axial stress is:

$$\sigma_r = \frac{.4}{1 - .4} 4,124 = 2,749 \text{ psi}$$

and with a coefficient of friction $\mu = .7$, the maximum axial frictional stress is:

$$\sigma_{f,ax} = .7 \times 2,749 = 1,925 \text{ psi}$$

From Table Xi the total friction area is:

$$A_f = 1.22 \times \pi(19.50) = 74.74 \text{ in}^2$$

and the maximum frictional resistance to pull-out becomes:

$$R_{p-o} = 1,925 \times 74.74 = 148,872 \text{ lbs.}$$

As an order-of-magnitude check on the maximum pull-out joint force, Dr. Takada found experimentally (Ref. 11, Fig.8):

$\emptyset = 200$ mm. $\quad P_u = 30$ tons

$\emptyset = 300$ mm. $\quad P_u = 40$ tons

and a parabolic relationship between pull-out force and displacement. Assuming a linear relation between P_u and $\emptyset$, Dr. Takada's results would give for our example:

$\overline{D} = D - t = 19.50 - .63 = 18.87'' = 479$ mm.

where t is the pipe thickness:

P_u = 30+ (40-30) x 279/100 = 57.9 tons = 127,300 lbs.

which is of the same order of magnitude as R_{p-o}.

iii. Joint rotation in bending

Dr. Takada (Ref. 11, Fig. 9) found experimentally, the following relationship between the pipe diameter and the ultimate moment at leakage:

Ø = 200 mm. M_u = 4 ton-m

Ø = 300 mm. M_u = 6 ton-m

with a leakage angle of 19^o.

From Table I the leakage angle is given by:

$$\tan \gamma = \frac{B}{D/2} = \frac{3.5}{(19.50 - .63)/2} = .371; \gamma = 20.53^o.$$

Assuming a linear relationship between M_u and Ø, M_u for our example becomes: M_u = 4+ (6-4) x 279/100 = 9.58 ton-m = 691,016 lb-in.

4. Failure Matrix Extension

By order of magnitude calculations of the type shown in this section, one can obtain a complete failure matrix of basic practical value. The uncertainties due to an almost complete lack of experimental data indicate, on one hand, the little confidence one should have on purely analytical results and, on the other, the need of tests on the ultimate static and dynamic strength of the various pipe joints.

It would seem clear even from the limited results of this interim report that failure of the cast-iron pipe itself could only occur due to corrosion or to the exceptional conditions encountered by pipe segments directly over faults. The main cause of failure in this type of pipe line, particularly under seismic conditions, must be due to the weakness of the joints,which is highly dependent on the time duration of the loads or displacements.

While this report indicates a methodology capable of assessing the sensitivity of pipelines to seismic motions, this methodology must now be made quantitatively accurate by obtaining the necessary experimental data on which to base it.

Table IV gives the Failure Matrix for the cast-iron pipe with mechanical joints (rubber gaskets) of this section and is typical of the matrices to be developed for other types of pipes and joints.

TABLE IV

FAILURE MATRIX

Cast-iron Pipe with Mechanical Joints (rubber gaskets)

	Ultimate Axial Tension lbs.	Maximum Elongation in.	Ultimate Axial Compression lbs.	Torsional Moment lb.-in.	Buckling Euler Column lbs.	Ring psi
Pipe	672,256	0.5	3,361,300	21,806,000	3,709,000	19,600

	Bending Rupture Moment lb.-in.	Ultimate Torsion Moment lb.-in.	Ultimate Transverse Shear lbs.	Ultimate Inner Pressure psi
Pipe	7,047,500	8,658,090	1,140,160	1,260

	Bolt Failure in Tension lbs.	Ultimate Tension Due to Friction lbs.	Bolt Failure in Bending lb.-in.	Ultimate Bending Moment (leakage)	Ultimate Leakage Angle Degrees	Ultimate Leakage Displ. in.
Joints	180,630	148,872	6,834,000	691,000	20°53	3.4

h. PART III - REFERENCES

1. Roger J. Carlsen; Troy F. Stroud; "Ductile Cast Iron Pipe and its Design," CIPRA.

2. Duane B. Ford; "Design Considerations for Underground Pipelines in Geologically Hazardens Areas;" CIPRA.

3. Roger J. Carlsen; "Thrust Restraint for Underground Piping Systems," CIPRA.

4. Troy F. Stroud; "Revised Ductile Iron Pipe Design Criteria," CIPRA.

5. Davis, H.E.; and F.N. Finn; "Trench Backfill Practices," J. AWWA, May, 1950.

6. Spangler M.G.; "Protective Casings for Pipe Lines," Iowa State Coll. Eng. Rept. 11, 1951-1952.

7. Spangler, M.G.; "Secondary Stresses in Buried High Pressure Lines," Iowa State Coll Eng. Rept. 23, 1954-1955.

8. Barnard, R.E.; "Design and Deflection Control of Buried Steel Pipe Supporting Earth Loads and Live Loads," Proc., ASTM, Vol. 57, 1957.

9. McClure, G.M.; "Secondary Stresses in Large-diameter Pipelines," Proc. Am. Soc. Civil Engrs., June 1957.

10. M.G. Spangler; "The Structural Design of Flexible Pipe Culverts," Iowa Engineering Experiment Station, December, 1941. Bulletin 153, Vol. XL No. 30.

11. S. Takada and S. Nagao; "Efficiency of Joint Parts for Aseismic Strength of Buried Pipelines," Proceedings of the Fourth Japan Earthquake Engineering Symposium (in Japanese), 1975, pp. 679-686.

APPENDIX A

```
100 PRINT
110 PRINT
120  PRINT 'ENTER MATERIAL TENSILE STRESS IN KSI'
130  INPUT S
140  PRINT 'ENTER MATERIAL RUPTURE MODULUS IN KSI'
150  INPUT R
160  PRINT 'ENTER OPERATING PRESSURE PSI'
170  INPUT P
180  PRINT 'ENTER PIPE DIAMETER IN INCHES'
190  INPUT D
200  PRINT 'ENTER PIPE THICKNESS IN INCH'
210  INPUT T
220  PRINT 'ENTER EQUIVALENT RING OVERBURDEN FORCE(W) LBS/FT.'
230  INPUT W
240  S=S*1000
250  R=R*1000
260 S1=P*D/(2*T)
270 Y=.0795*(D+T)/(T**2)
280 S2=Y*W
290 X=2*S*T/D
300 Q=SQR((X-P)/X)
310 W1=R*Q/Y
320 Z=S1+S2
330 Z1=S1+(S2*S/R)
340 Z2=W1/W
350 Z3=S/Z1
351 PRINT
360  PRINT 'DATA ECHO (W NOT PRINTED)'
370 PRINT S;R;P;D;T
380  PRINT
390  PRINT
400  PRINT 'RESULTS : STRESSES AND SAFETY FACTORS'
410  PRINT
411 PRINT
420  PRINT 'TENSILE STRESS DUE TO OPERATING PRESSURE'
430  PRINT S1
440  PRINT 'BENDING STRESS DUE TO OVERBURDEN'
450  PRINT S2
460  PRINT 'COMBINED TENSION + BENDING STRESS'
470  PRINT Z
480  PRINT 'ADJUSTED COMBINED STRESS INCLUDING NON-LINEAR EFFECTS'
490  PRINT Z1
500  PRINT 'SAFETY FACTOR=MAX TENSILE STRENGTH/ADJ. COMBINED STRESS'
510  PRINT Z3
520  PRINT 'APPLIED EQV.RING FORCE    '
530  PRINT W
540  PRINT 'MAX. EQV.RING FORCE    '
550  PRINT W1
560  PRINT 'LOAD FACTOR=MAX RING FORCE(W1)/APPLIED RING FORCE(W)'
570  PRINT Z2
571  PRINT
572  PRINT
580 PRINT 'DO YOU WANT TO SOLVE ANOTHER CASE ? YES/NO'
590  INPUT A$
600  B$='Y'
610  IF A$=>B$ THEN 100
620 END
630 STOP
```