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PROBABILISTIC ASSESSMENT OF WELD QUALITY IN STEEL PIPING UNDER SEISMIC CONDITIONS

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DISCLAIMER

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SUMMARY

Seismic stress analyses of plant piping systems usually ignore the possibility of reduced joint strength due to weld imperfections. This paper presents a method that might be used to assess the impact of weld imperfections in a piping system, provided that limited destructive examination of welded joints is possible. A probability distribution function of weld quality is developed from the destructive examination, and this is combined with an experimentally determined relationship between weld quality and reduced strength. This latter is the result of uniaxial tensile testing of specimens with controlled imperfections. A seismic stress probability distribution function is determined by conventional seismic analysis. The above quantities are used to quantify the conditional failure probability of the imperfect weld. Effect of imperfection distribution within a given weld on the probability of failure is discussed.

* The information contained in this article was developed during the course of work under Contract No. DE-AC09-76SR00001 with the U.S. Department of Energy.

1.0 INTRODUCTION

Modifications to a plant piping system used to distribute secondary cooling water yielded a statistically large number of discarded welded joints that could be examined destructively to quantify the weld imperfections. A seismic stress analysis was available for a companion piping system with welds made to the same specification. The objective of this study was to assess the probability that a weld would fail under seismically induced stress in the companion system, assuming that the weld quality was statistically the same as that determined from the destructive examination. In order to assess the failure probability, four procedures are involved. The first procedure included characterization of weld quality which was achieved by a single dimensionless quantity, the fraction of cross sectional area reduction due to all imperfections. The data is processed to produce a weld quality probability distribution function. The second is an analytical procedure which provides piping systems seismic stress data under a design basis earthquake. A seismic stress probability distribution function results from the second procedure. Uniaxial tensile testing of steel samples containing controlled imperfections is the work of the third procedure. This is done in order to obtain nominal failure stress of an imperfect weld as a function of its quality. The fourth and final procedure computes the failure rate per weld due to a given earthquake. The effect of imperfection distribution within the weld on that weld failure probability is also addressed.

2.0 WELD QUALITY CHARACTERIZATION

The selected measurement of weld quality is defined by the dimensionless quantity x; where,

$$x = \Delta A/A \quad (1)$$

and

ΔA: Weld imperfection measured as a reduction of the cross sectional area at the pipe weld, in.^{2} and

A: Nominal pipe metal cross sectional area, in.^{2}.

One hundred girth welds were examined in this investigation. The welds were obtained from piping removed due to plant modifications. The piping varied in diameter from 6.625" to 24.0" O.D. Pipe dimensions (O.D., nominal wall thickness and cross sectional area A) are tabulated for this study in Table I. Each weld was sandblasted and completely radiographed. Weld imperfections were identified from examinations of radiography. Those imperfections requiring closer examination were marked for sectioning. For most weld imperfections, depth of the imperfection into the weld thickness was directly measured from a photograph of a polished section cut in a perpendicular direction to the weld imperfection. For some imperfections, however, the cross sectional area of the imperfection was directly measured from detailed photographs using an Omnicon FAS 2 Image Analysis System.[1] The reduction in the weld cross sectional area, A, is the sum of all the individual imperfections cross sectional areas found in that weld. The cross sectional area of one imperfection is equal to the product of the circumferential length of that imperfection and its depth normal to weld thickness. The weld imperfection reduction ratio, x, was then calculated for each girth weld in accordance to equation (1). Although weld crown (reinforcement) for each weld did exist in all cases, it was not considered in calculating the nominal pipe cross sectional area at weld location. Weld crown increases weld cross sectional area; thus, it is conservative to ignore weld reinforcement in all cases. The weld imperfections were found to vary from 0.005 to 0.332.

3.0 WELD QUALITY PROBABILITY DISTRIBUTION

Table II shows the frequency distribution of the weld imperfection reduction ratios, x. Using standard statistical methods as outlined in Ref. 2, a one-sided tolerance limit is calculated. It is estimated that 99% of the weld population from which the weld samples were taken will have imperfections less than the sample maximum x value, with 95% confidence. The weld quality probability distribution $P_1(x)$ is idealized as shown in Figure 1. The area under the curve $P_1(x)$ vs. x between x=0.0 and x=0.332 is 0.99. The remainder of the area under the curve between x=0.332 and x=1.0 is, therefore, 0.01. This indicates a 1% exceedance of weld quality over the maximum x value observed in the sample. $P_1(x)$ is idealized as a piece-wise linear function to facilitate the integration required to calculate the probability of weld failure.

4.0 SEISMIC STRESS PROBABILITY DISTRIBUTION

The piping systems containing imperfect welds were analyzed for the seismic stresses due to a design basis earthquake. The analyses followed established linear elastic methods, using finite elements techniques to compute the stresses at discrete nodal points along the piping systems. Examining the results of these analyses for several systems indicated that at least 99% of the nodal points calculated stresses are below the piping material yield stress σ_y, with only 1% of them exceeding σ_y, but are less than the material ultimate strength, σ_u. The seismic stress probability distribution $P_2(\sigma)$ is assumed to be piece-wise linear function as shown in Figure 2(a). The area under the probability curve $P_2(\sigma)$ vs. σ between $\sigma=0$ and σ_y is 0.99, while the area is equal to 0.01 between σ_y and σ_u. The seismic stress probability distribution is next modified to account for the non-uniform normal flexural stresses induced in a seismic event.

The reason for the modification is that the calculated stress occurs in the extreme fiber of the piping cross section. The stress in the piping tensile zone varies between the extreme fiber stress and zero (at the neutral axis). Because weld imperfections can occur anywhere around the pipe circumference, not exclusively at the extreme fiber, the equivalent uniform pipe normal stresses are calculated and the stress probability distribution is accordingly modified.

4.1 Equivalent Uniform Stresses

In Figure 3, consider a piping cross section with inside radius, R and wall thickness, t. The resulting stress distribution due to flexure, M, is also shown in Figure 3. The extreme fiber stresses are assumed to be equal to material yield stress, σ_y. The incremental force, dF_t is given& by:

$$dF_t = \sigma dA \quad (2)$$

where:

σ: is the stress at a distance y from the neutral axis; and

dA: is the incremental area of the pipe cross section at the stress level, σ. σ and dA are given by equations (3) below

$$\sigma = My/I \quad (3)$$

$$dA = Rt\, d\theta$$

where: I is the moment of inertia.

Substituting equations (3) into (2), the following results:

$$dF_t = \frac{M}{I} R^2 t \, Sin\theta d\theta \tag{4}$$

Total tensile force F_t is given by:

$$F_t = \frac{M}{I} R^2 t \int_o^{\pi} Sin\theta d\theta = 2Rt\sigma_y \tag{5}$$

The equivalent uniform flexural stress, $_e$ is defined as the total cross section tensile force, F_t divided by the total tensile area, πRt. Hence,

$$\sigma_e = \frac{2\sigma_y}{\pi} \tag{6}$$

Using equation (6), the seismic stress probability distribution is modified accordingly as shown in Figure 2(b).

5.0 WELD QUALITY STRESS RELATIONSHIP

A series of uniaxial tensile specimens were made from a similar material to the actual piping. The specimens were machined to contain controlled reduction of areas to simulate weld imperfections. These specimens were tested in a universal testing machine to failure. The loading at failure vs. the area reduction ratio x is shown in Figure 4. Also shown in this figure is a schematic of a typical specimen. This relationship is conservative for two reasons. First, imperfections in welds are randomly distributed while the machined imperfections in the tensile specimens are controlled and concentrated in one location. This produced a conservative loading-imperfection relationship. The second reason is that the tensile specimens are made of the base metal which has lower strength than the weld metal used, thus yielding a lower failure loading.

6.0 WELD FAILURE PROBABILITY ASSESSMENT

The failure rate per weld, F, due to a given design basis earthquake is given by:

$$F = \int_{0}^{1} P_1 (x)\, dx \int_{\sigma}^{\sigma_u} P_2 (\sigma)\, d\sigma \tag{7}$$

The quantities $P_1(x)$, $P_2(\sigma)$ were obtained earlier in sections 3.0 and 4.0. The lower limit of the second integration, σ, is the failure stress corresponding to a given weld imperfection as determined by the tensile tests and shown in Figure 4. For simplicity, the x and σ relationship is assumed linear (idealized function shown in Figure 4). This modification is conservative since at a given value of weld imperfection, x, the linear relationship gives a lower loading for weld failure, so the imperfect weld failure probability increases. It is noted that the F value as obtained from equation (7) considers all possible weld failure stresses ranging from its reduced failure stress to the material ultimate strength, σ_u (second integration) for all potential weld imperfection ratios ranging from 0 to 1 (first integration).

To account for the weld imperfection distribution around the weld circumference, the uniformly distributed imperfection ratio x is modified by

$$x^* = \frac{nx}{0.5 + (n-0.5)x} \tag{8}$$

where

x^* is the modified weld imperfection reduction ratio of a non-uniform weld imperfection distribution, and

n is a measurement of imperfection concentration in the piping cross section.

The relation between x and x^* is shown in Figure 5 for different values of n. When n=0.5, $x=x^*$ indicating that the imperfection is uniformly distributed along the circumference. At the other extreme, when n=1.0, the total imperfection is assumed to be concentrated at the most unfavorable location on the tensile side of the pipe cross section.

Using relationship (8), the imperfection probability distribution $P_1(x)$ is modified for various values of n. The failure probability was then calculated according to equation (7). The resulting weld failure probability F for different concentration of weld imperfection in the pipe tensile side is shown in Figure 6. As can be seen from this figure, the failure probability is not sensitive (it is in the order of 10^0 rather than 10^1) to the imperfection distribution around the girth weld circumference. When the total weld imperfection is assumed to concentrate in the tensile zone of the pipe cross section, the weld failure probability F was calculated to be about twice as likely as the failure probability if the imperfections were uniformly distributed around the girth weld circumference.

7.0 CONCLUSIONS

A methodology to calculate failure probability of imperfect welds in piping systems under seismic conditions has been introduced. Determination of weld quality probability, stress distribution probability and quantification of reduced load bearing capabilities in relation to reduced weld cross sectional area are essential parts in calculating the failure probability. Numerical integration of the failure probability expression (equation 7) allows the use of probability distribution functions to represent the piping system under consideration. Imperfections distribution within a weld was found to have little influence on that weld failure probability.

8.0 ACKNOWLEDGEMENT

The experimental and weld characterization work of G. S. Dsouza, R. E. Sprayberry of Savannah River Plant and L. P. McCabe of Savannah River Laboratory in support of this investigation is gratefully acknowledged by the authors.

9.0 REFERENCES

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2. U.S. Department of Commerce, National Bureau of Standards, Experiment Statistics, Handbook 91, Chapter 2 (August 1963).

LIST OF TABLES

TABLE I: Pipe Dimensions of Welds Obtained for Weld Quality Characterization

Weld No.	Pipe O.D. (in.)	Thickness (in.)	Cross Sectional Area (in.^{2})
1- 77	6.625	0.28	5.58
78- 84	10.75	0.25	8.25
85- 86	13.00	0.25	10.01
87- 90	18.00	0.25	13.94
91	18.00	0.312	17.34
92- 96	24.00	0.375	27.83
97	12.75	0.33	12.88
98-100	13.00	0.33	13.13

TABLE II: Frequency Distribution of Weld Reduction Ratio, x.

No. of Welds	Weld Area Reduction Ratio, x
14	0 - 0.05
45	0.05 - 0.10
21	0.10 - 0.15
8	0.15 - 0.20
9	0.20 - 0.25
1	0.25 - 0.30
1	0.30 - 0.35

FIGURE TITLES

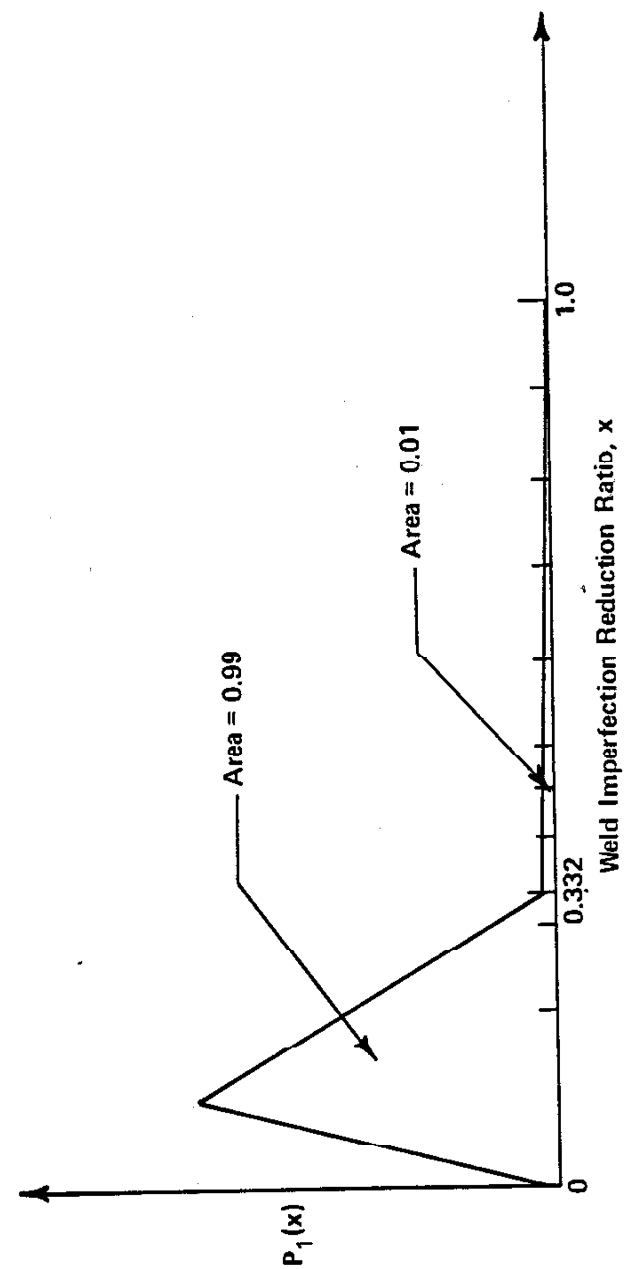
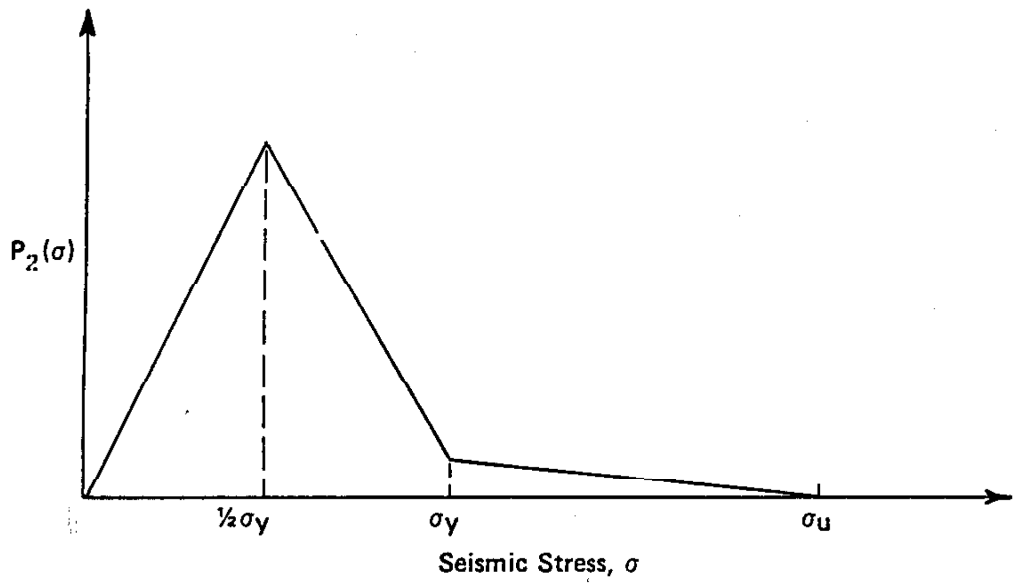
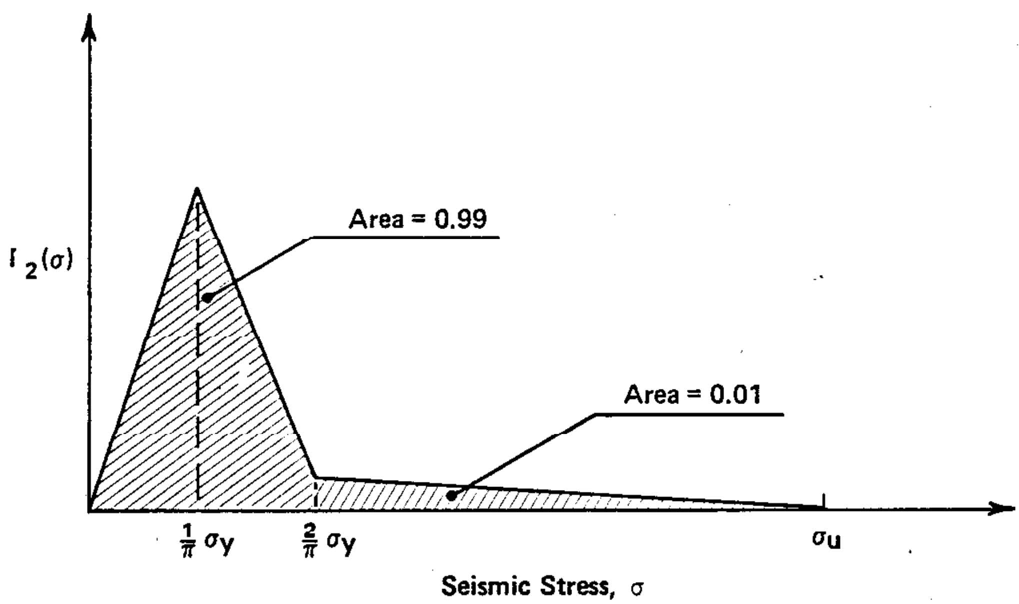


FIGURE 1. Weld Quality Probability Distribution



(a): Seismic Stress Probability Distribution



(b): Modified Seismic Stress Probability Distribution

FIGURE 2. Seismic Stress Probabiltiy Distribution

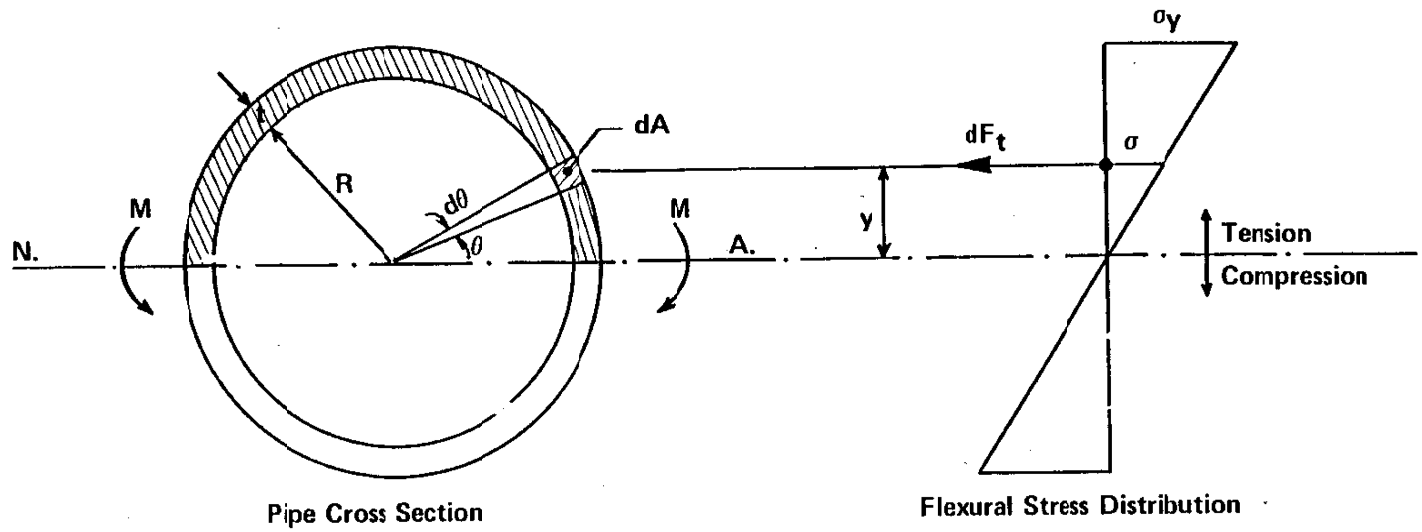


FIGURE 3. Flexural Stress Distribution

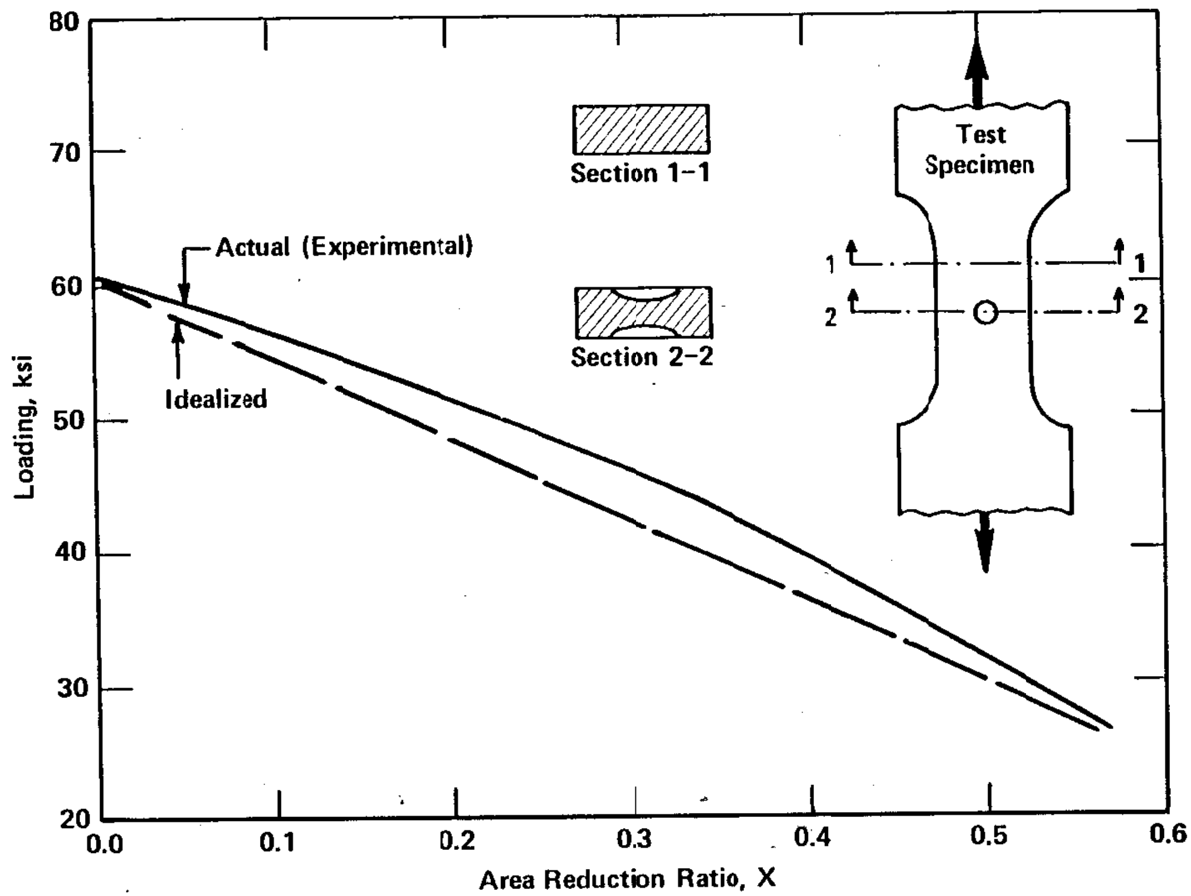


FIGURE 4. Experimental Relationship Between Specimens Failure Loading and Area Reduction Ratio

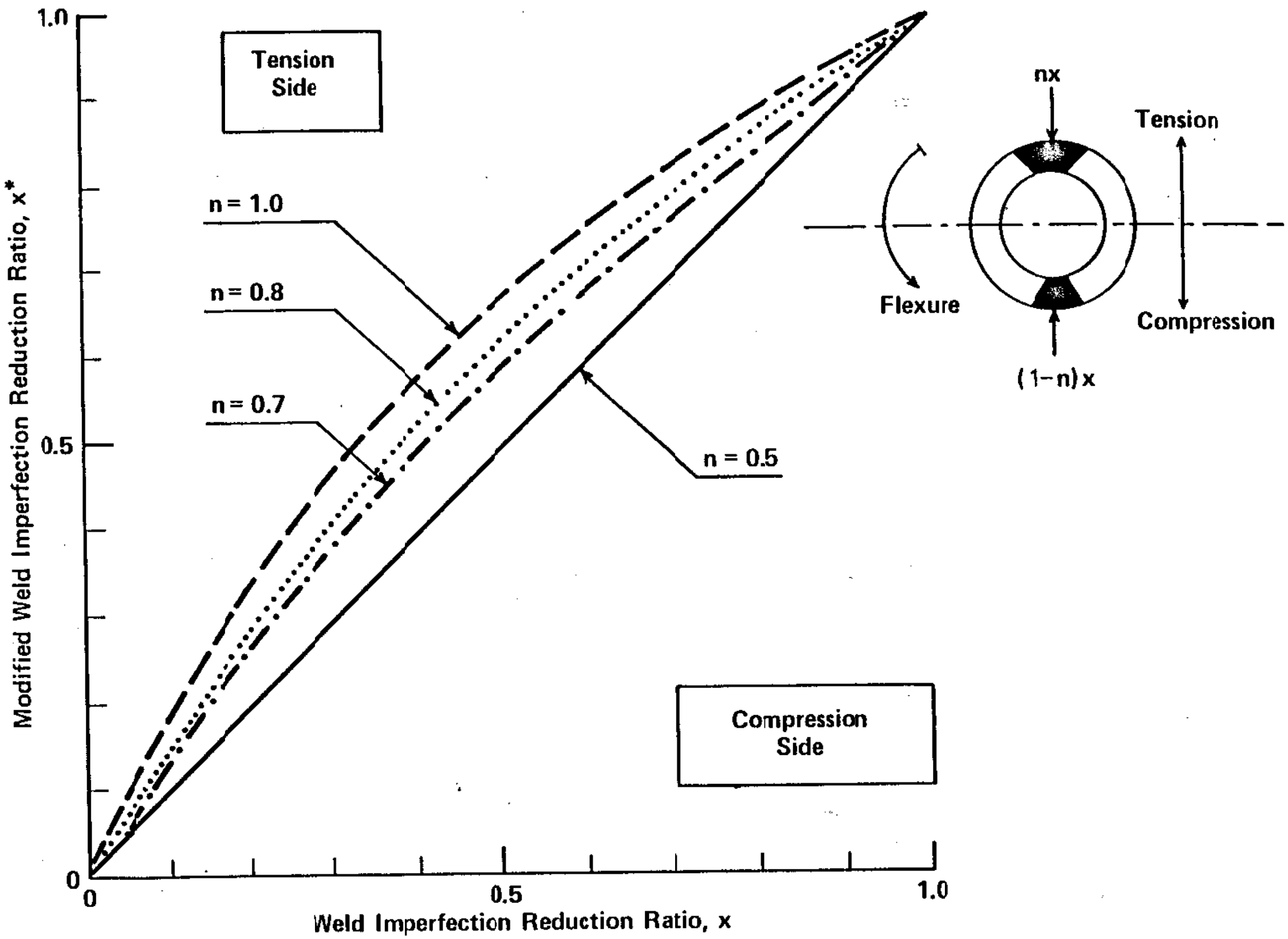


FIGURE 5. Relationship Between x and x* for Different Values of n

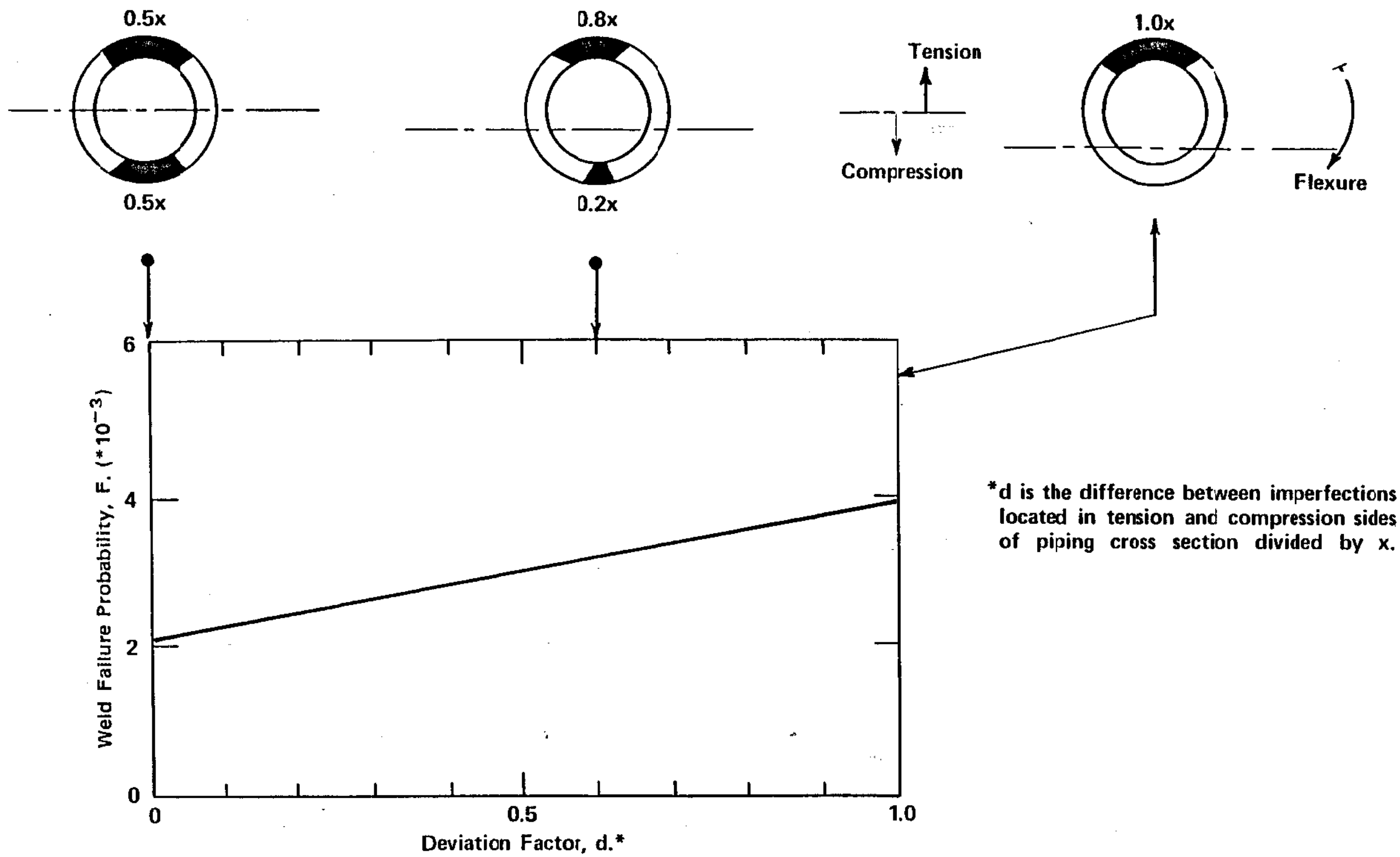


FIGURE 6. Effect of Weld Imperfection Distribution on Weld Failure Probability