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RELIABILITY OF ELECTRIC CABLES AND CONDUIT SUPPORTS

by

Andrzej S. Nowak[1] and Peria V. Regupathy[2]

SUMMARY

Reliability of structures supporting electrical cables and conduits in nuclear power plants is evaluated. Typical supports are usually made of cold-formed channels joined by means of spot welds to form various configurations.

Structural load includes support weight, weight of cables and conduits as well as dynamic forces due to earthquake. Resistance depends on strength of base metal and welds. It is modeled from test data.

Reliability is measured in terms of the reliability index.

INTRODUCTION

In power plants the electrical cable and conduit supports are integral parts of the structural system. Their failure may cause failure of other components, structural or nonstructural. Such failures may adversely affect the control systems of the entire plant. The problem is specially important in the case of nuclear power plants, because of more serious consequences of failure compared to conventional power plants.

Typical supports of cables and conduits are made of cold-formed channels as shown in Figure 1. Connection between channels are accomplished by spot welding, Ref. 4. Examples of some possible combinations using C-sections are presented in Figure 2.

The supports are subject to dead load (own weight as well as the weights of cables or conduits they bear) and earthquake forces.

Evaluation of the structural adequacy of such structures is best approached by means of probability concepts. Both loads and resistances can be considered as random variables. The objective of this study is to evaluate the reliability of the supports. Safety is measured in terms of a reliability index. In this paper the approach which has been developed is verified using test data.

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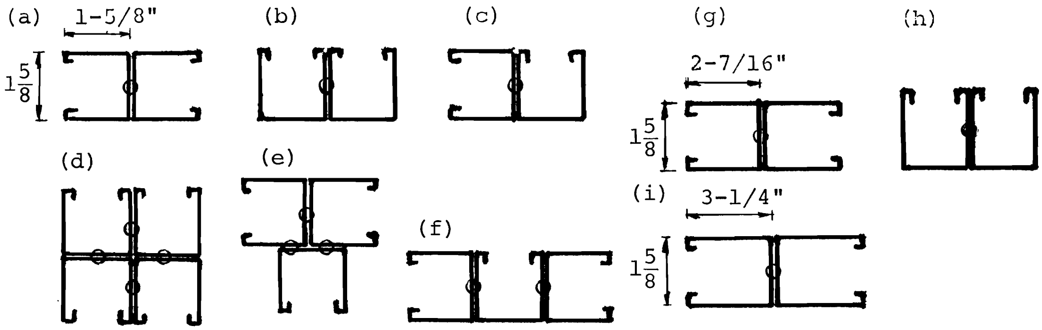
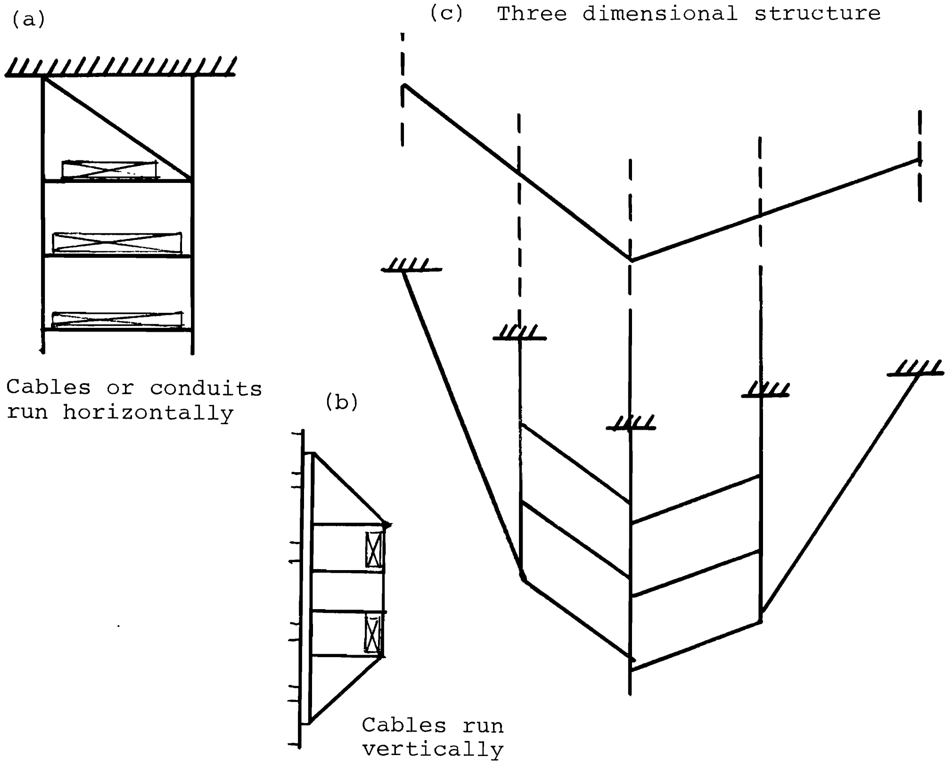


Fig. 1 Typical Cross Sections of Support Members; Spot Welds are Denoted by O



Cables or conduits run horizontally

Cables run vertically

Three dimensional structure

Fig. 2 Typical Configurations of Supports

SAFETY MEASURE

A structure performs its function without failure if resistance exceeds load effect.

Probability of failure, P_F, is

$$P_F = \text{Prob}\ (R<Q) \tag{1}$$

where

R = resistance,
Q = load effect.

R and Q can be expressed as functions of various parameters (dimensions, strength of material, load components, etc). However, the direct calculation of P_F, using eq. 1, in practical cases, is either very difficult or may be impossible.

In this study safety is measured in terms of a reliability index. The procedure follows the method described in detail in Ref. 2. A summary of the method follows.

Resistance, R, is considered a random variable with the cumulative distribution function (CDF), F_R, and probability density function (PDF), f_R. All load components are lumped into one random variable, Q, with the CDF, F_Q, and PDF, f_Q.

Let $Z = R-Q$, then from eq. 1,

$$P_F = \text{Prob}\ (Z<0) \tag{2}$$

If R and Q are normal then Z is also normal with the mean $\bar{Z} = \bar{R} - \bar{Q}$, where bars indicate mean values, and with standard deviation $\sigma_Z = (\sigma_R^2 + \sigma_Q^2)^{1/2}$, where σ_R and σ_Q are standard deviations of R and Q, respectively. The probability of failure is

$$P_F = \Phi\left(-\frac{\bar{Z}}{\sigma_Z}\right) \tag{3}$$

where Φ is the standard normal distribution function. The ratio of $\bar{Z}/\sigma_Z$ is denoted by β and it is called the reliability index.

If R and/or Q are not normal then the Rackwitz/Skov approach is applied, Ref. 2. The non-normal distributions are approximated by normal with the same CDF and PDF value at the so called "design point." In the theory of structural safety the design point, (R^*, Q^*), is a point on the boundary between safe realization and failure. The equations for R^* and Q^* are

$$R^* = \bar{R} - \alpha_R \beta\, \sigma_R \tag{4}$$

$$Q^* = \bar{Q} + \alpha_Q \beta \sigma_Q \tag{5}$$

where

$$\alpha_R = \sigma_R / (\sigma_R^2 + \sigma_Q^2)^{1/2},$$

$$\alpha_Q = \sigma_Q / (\sigma_R^2 + \sigma_Q^2)^{1/2}$$

The algorithm to calculate β, R^* and Q^* is given in Figure 3. In the algorithm φ denotes the standard normal density function.

LOADS

Dead load, D, includes own weight of channels (2 to 3 lb/ft, 30 to 45 N/m) ,fittings (2 to 4 lb, 10 to 20 N, per item) and cables (20 to 70 lb/ft, .3 to 1 KN/m) or conduits (up to 40 lb/ft, .6 KN/m). D constitutes 20 to 80% of the total load. It is assumed that D is normally distributed, with the mean to nominal ratio equal to 1.0 and the coefficient of variation 10%.

The other load component affecting supports is earthquake, E. Seismic forces are derived from site spectra and building properties. Site spectra are selected based on geological site conditions and records of seismic activity in the region. Floor response spectra are developed from mathematical simulation of the structural stiffness, mass and foundation media when subjected to an acceleration time history representing the site spectra. Based on the natural frequency and damping properties of any given structure, the seismic accelerations are obtained from the appropriate floor spectra.

Probabilistic model for earthquake load is based on the results presented in Ref. 3. It is assumed that E has a Type II extreme value distribution,

$$F_E(x) = \exp[-(uE/x)^k] \tag{6}$$

where

E = nominal earthquake, as defined by the Uniform Building Code (5),

k = 2.3, which corresponds to the coefficient of variation of about 140%,

u = depends on geographical location, for example it is .0184 for Massachussetts and .0825 for the Los Angeles area.

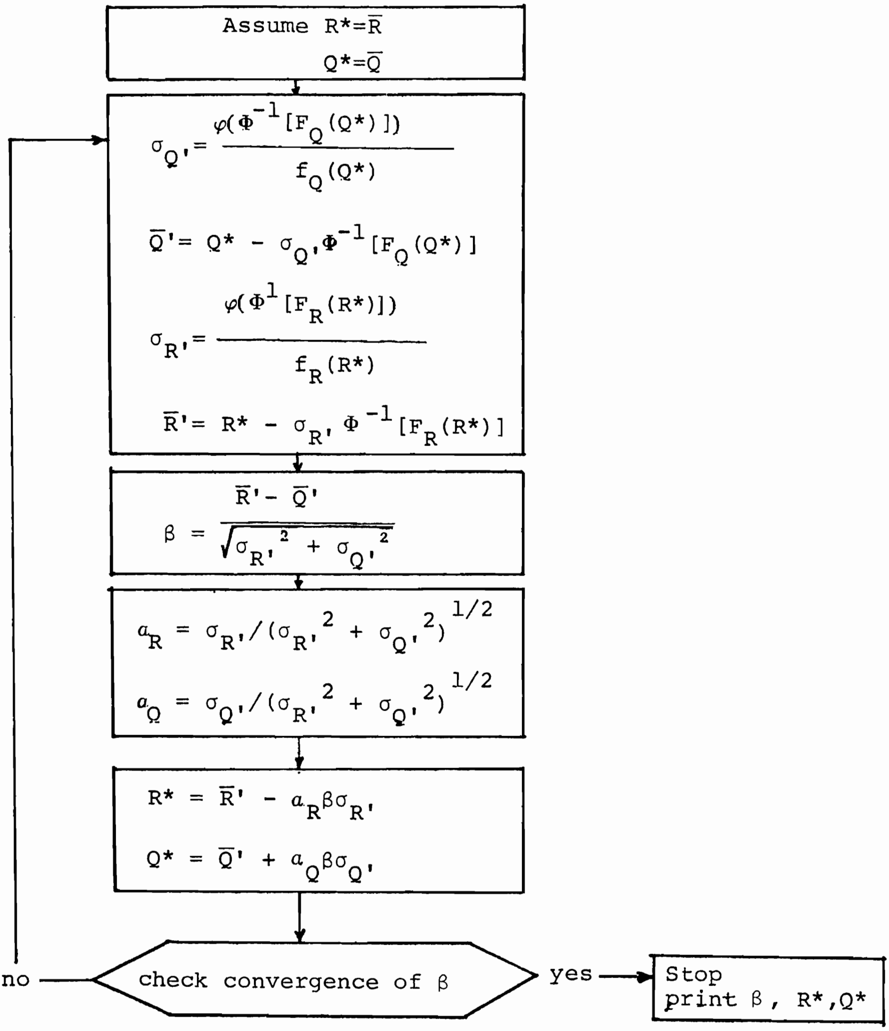


Fig. 3 Algorithm to Calculate a Reliability Index

Distributions for $Q = D + E$ are plotted on normal probability paper in Fig. 4 for the Massachussetts and the Los Angeles areas, using three ratios of D to E: 1:3, 1:1 and 3:1.

RESISTANCES

The distributions are modelled on the basis of test data. Two limit states are considered: tension in axially loaded members as well as bending and/or shear.

In the analysis the geometry of sections is considered as deterministic and material properties are represented by the yield stress only. Yield stress values were determined for 60 coupons from randomly selected channels. Also tested were coupons from cable tray elements, 31 from the channels and 31 from the rungs, Fig. 5. Typical load-deformation plots are shown in Fig. 7. The results are plotted on normal probability paper in Fig. 7, 8 and 9 for channels, cable tray channels and cable tray rungs, respectively. Modeled distributions are also shown in the figures.

It has been found that the resistance of interconnected channels subject to bending and/or shear is determined by the shear strength of spot welds. Therefore the welds were tested; one weld at a time. Also the spot welds connecting rungs to channels in cable trays were tested, two at a time. Typical load-deformation relationship is shown in Fig. 10. The results are plotted on normal probability paper in Fig. 11 to 14, for various sections of channels and in Fig. 15 for cable trays. Modeled distributions are also plotted.

RELIABILITY INDICES

The calculations followed procedure outlined in Fig. 3.

For channels and cable trays the distributions of R are shaped as modeled distributions in Fig. 7 to 9. Load distributions are given in Fig. 4. AISI (1) design interion for tension members is

$$\max\,[\,D,\ .75(D+E)] \le .6\ F_y \qquad (7)$$

where D and E are tensile stresses due to dead load and earthquake, and F_y is yield stress for base metal. The specified value of F_y is 33 Ksi (230 Mpa) for channels and 30 Ksi (200 MPa) for cable trays.

The resulting reliability indices are given in Table 1.

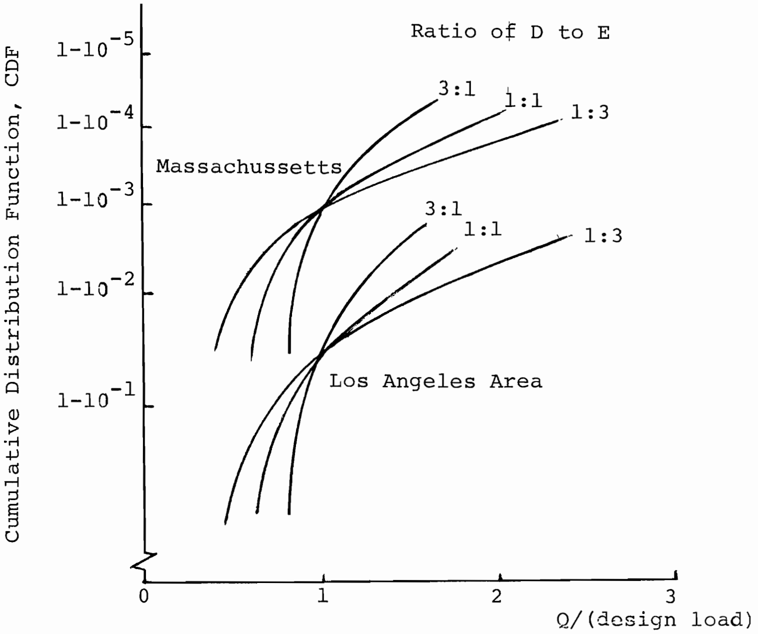


Fig. 4 CDF for Total Load, Q

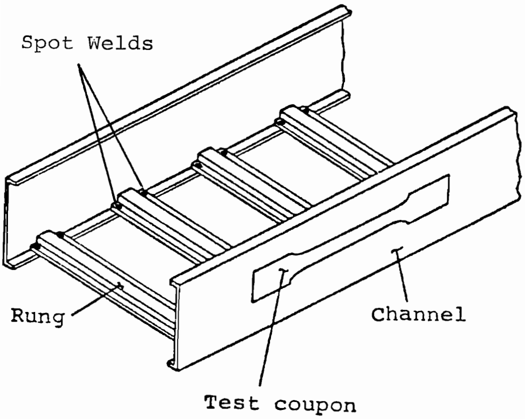


Fig. 5 Cable Tray

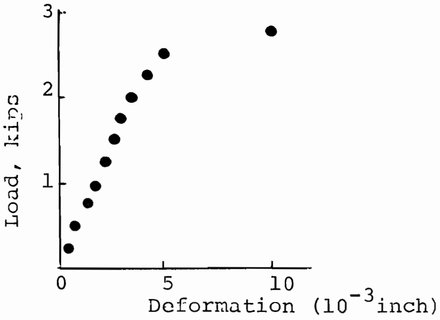


Fig. 6 Typical Load-Deformation Plot for Base Metal

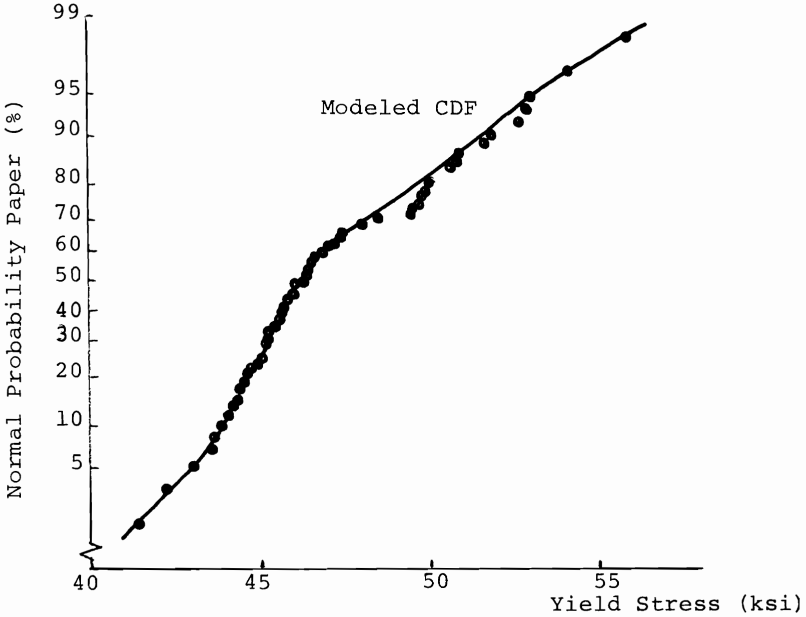


Fig. 7 Test Results and Modeled CDF for Base Metal of Channels

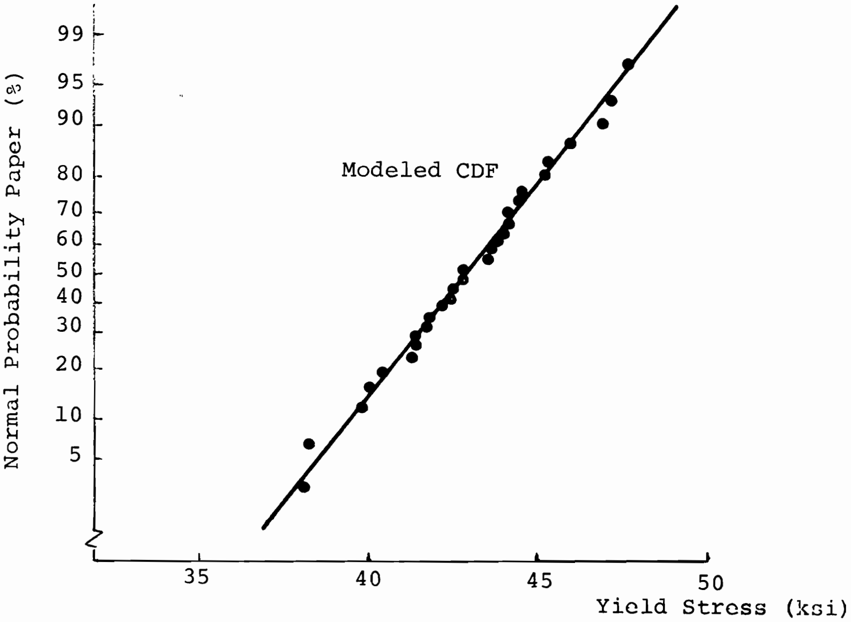


Fig. 8 Test Results of Modeled CDF for Base Metal of Cable Tray-Channels

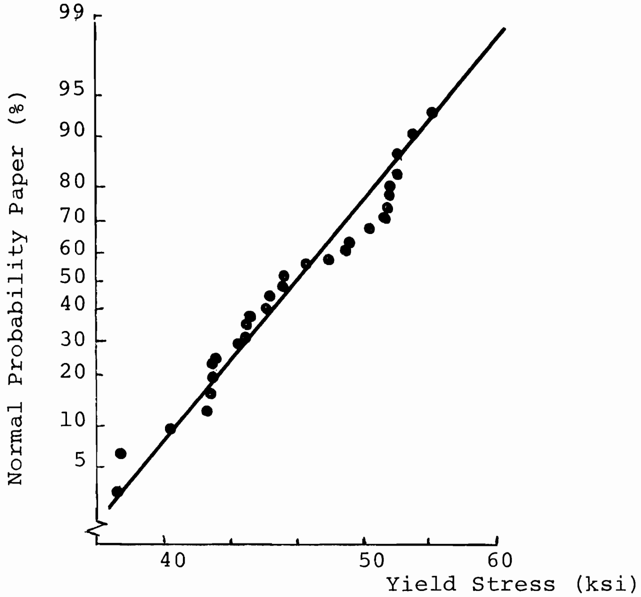


Fig. 9 Test Results and Modeled CDF for Base Metals of Cable Tray-Rungs

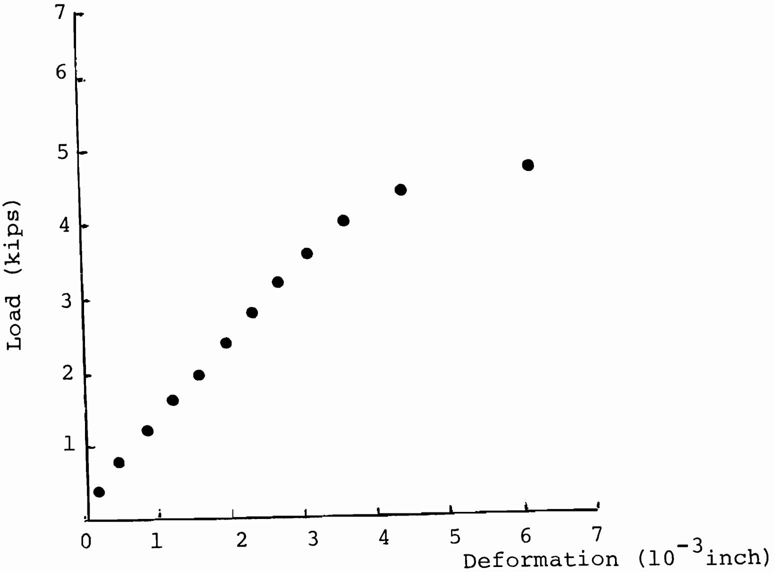


Fig. 10 Typical Load-Deformation Plot for Spot Welds

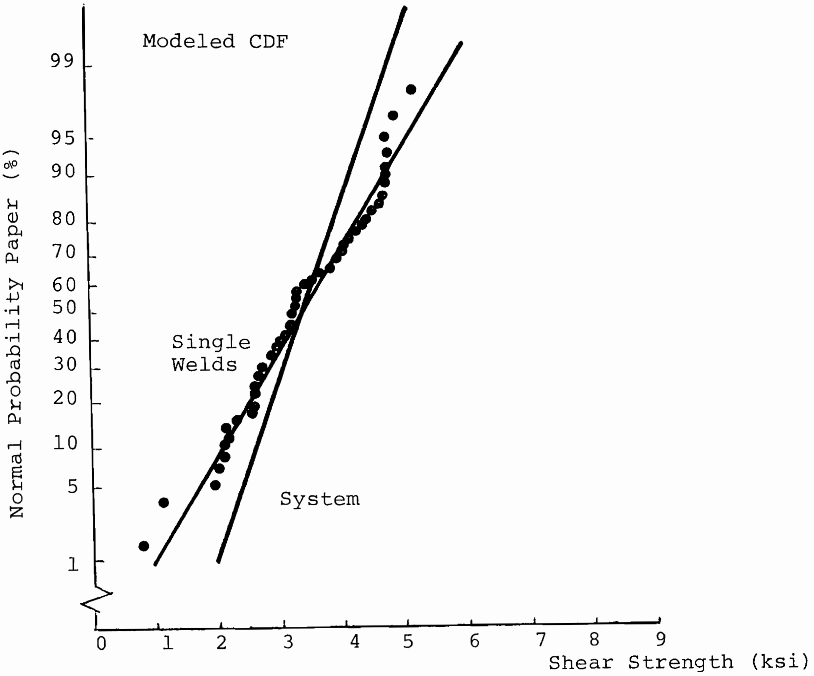


Fig. 11 Test Results and Modeled CDF for Back-to-Back Spot Welds, Fig. 1(a)

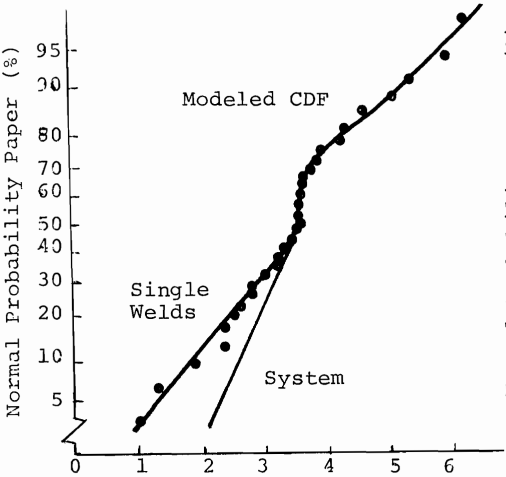


Fig. 12 Test Results and Modeled CDF for Side-to-Back Spot Welds

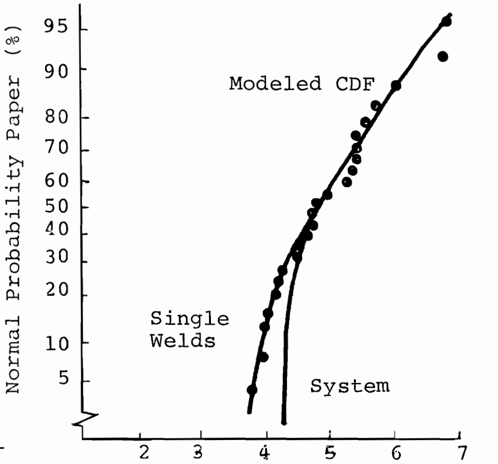


Fig. 13 Test Results and Modeled CDF for Side-to-Side Spot Welds

For spot welds AISI (1) design interion is

$$\max [D, .75(D+E)] \leq \text{allowable shear strength} \qquad (8)$$

where D and E are shear stresses in the spot weld due to dead load and earthquake.

The allowable shear strength depends on the thickness of the thinnest outside sheet. The thickness of channels is .1046 in (2.64 mm) and the corresponding allowable shear strength is 1570 lb or 6.98 kN. The thickness of cable tray material is .0598 in (1.51 mm) and the corresponding allowable shear stress is 721 lb or 3.20 kN.

Load distributions for spot welds are the same as for channels and cable trays. CDF's for resistance of a single spot weld are given in Fig. 11 to 15.

Typically the welds connecting channels are spaced at 3 inch (7.5 cm). The minimum number of spot welds in a member is 3. The tests demonstrated plastic properties of welds (yielding), Fig. 10. This allows for plastic redistribution of load between adjacent spot welds.

The correlation between welds in a line has been analyzed visually. The fused areas were compared. For example, the photographs of three cross-sections of welds used to join two channels as in Fig. 1 (a) are shown in Fig. 16.

Reliability indices were calculated separately for single welds and for three-and-more weld systems of uncorrelated welds. For multiple welds the distribution functions of resistance were calculated using convolution functions (Ref. 6). The modeled CDF's for the systems are also plotted in Fig. 11 to 14. For cable trays a system of four double welds is considered. The actual β's are between those for single welds and systems. Their values can be interpolated on the basis of the degree of correlation. The results are listed in Table 2.

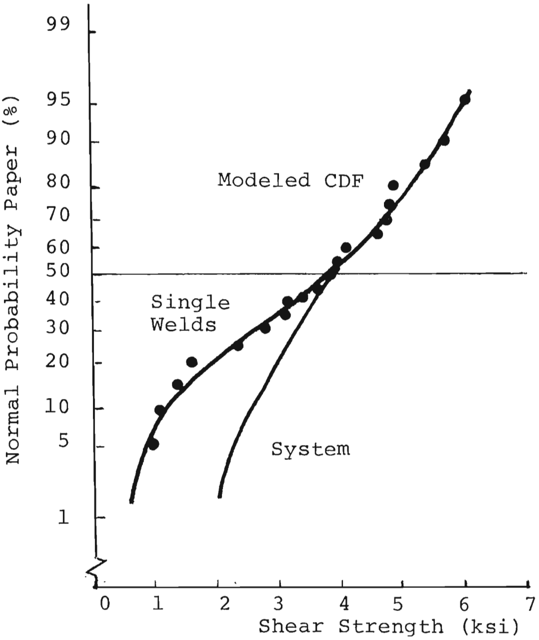


Fig. 14 Test Results and Modeled CDF for Side-to-Side Spot Welds, Fig. 1(h)

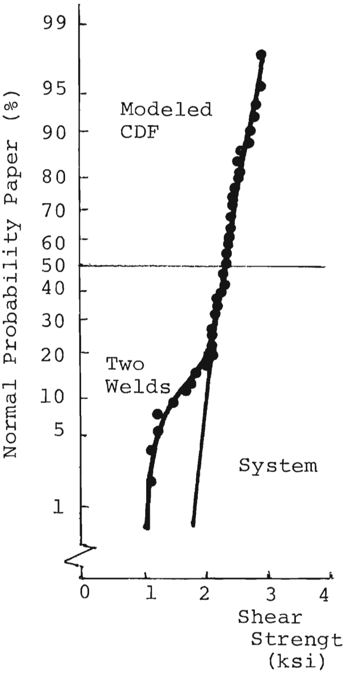


Fig. 15 Test Results and Modeled CDF for Spot Welds in Cable Trays, Two Welds at a Time

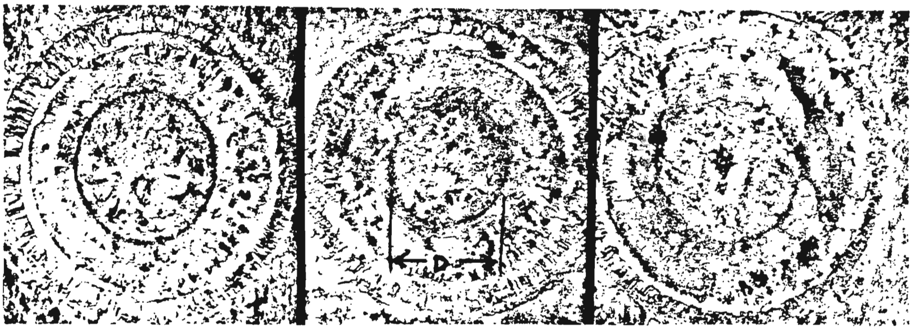


Fig 16. Photographs of Back-to-Back Spot Welds. D is Diameter of the Fused Area

TABLE 1, RELIABILITY INDICES FOR TENSION MEMBERS

	Ratio of D to E					
	Massachussetts			Los Angeles Area		
Items	1:3	1:1	3:1	1:3	1:1	3:1
Channel sections	4.06	4.26	5.73	3.25	3.48	3.75
Cable trays-channels	4.06	4.26	5.73	3.25	3.48	3.75
Cable trays-rungs	4.14	4.36	4.67	3.34	3.58	3.90

TABLE 2, RELIABILITY INDICES FOR SPOT WELDS

	Ratio of D to E					
	Massachussetts			Los Angeles Area		
Spot Weld Type	1:3	1:1	3:1	1:3	1:1	3:1
Single, back-to-back, Fig. 1(a)	2.59	2.14	1.69	2.50	2.06	1.69
System, back-to-back, Fig. 1(a)	4.34	3.58	2.76	4.18	3.48	2.76
Single, side-to-back, Fig. 1(f)	2.91	2.66	2.38	2.85	2.62	2.38
System, side-to-back, Fig. 1(f)	6.55	5.91	5.22	6.41	5.82	5.22
Single, side-to-side, Fig. 1(b)	4.19	4.44	4.69	3.39	3.67	4.10
System, side-to-side, Fig. 1(b)	4.30	4.58	4.88	3.52	3.84	4.39
Single, side-to-side, Fig. 1(h)	1.92	1.62	1.29	1.85	1.58	1.29
System, side-to-side, Fig. 1(h)	3.32	2.80	2.23	3.20	2.73	2.23
Two, cable tray welds	4.47	3.78	3.69	2.69	2.78	2.97
System, cable tray welds	4.29	4.57	4.87	3.51	3.82	4.37

CONCLUSIONS

1. Safety was evaluated for tension members and spot welds in cable and conduit supports, designed according to the AISI specification.

2. Yield stress values seem to be underestimated, reliability indices for tension exceed 4 for Massachussetts.

3. Spot weld strength seems to be overestimated in the specification. A strong correlation was observed between the shear strength and type of weld (back-to-back or side-to-side) and size of the channel. This is the result of technological process (type of electrode used, its length and angle of application).

4. Fused areas were compared for adjacent spot welds. A strong effect of the technological process has been observed. For example, section (a) in Fig. 1 is connected by four different electrodes, so that any four consecutive welds are uncorrelated. Welds in other sections, done by single electrodes, seem to be strongly correlated.

ACKNOWLEDGEMENTS

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APPENDIX-REFERENCES

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APPENDIX-NOTATION

D = dead load,
E = earthquake effect,
F = cumulative distribution function,
F_y = yield stress of base metal,
F = probability density function,
k = coefficient in eq. 6,
P_F = probability of failure,
Q = total load,
R = resistance,
u = coefficient in eq. 6
Z = $R - Q$,
α = sensitivity factor in eq. 4 and 5,
β = reliability index,
Φ = standard normal distribution function,
σ = standard deviation,
φ = standard normal density function

Superscripts:

$*$ = design point,
$-$ = mean value.