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A STUDY OF THE PRELOAD RELATIONSHIP IN BOLTING TECHNOLOGY: EXPERIMENTAL DESIGN AND ANALYSIS

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ABSTRACT

This report presents the results of an exploratory investigation on preload funded by the Bolting Technology Council (BTC). Of the large number of factors that are thought to affect the torque/tension (preload) relationship, eleven factors, considered to be the more critical, have been selected for inclusion in the investigation. Using a statistical approach, a two-level screening experiment was thus designed. Simple experimental rigs were fabricated involving a single bolt with a combination of solid plates, spacers, Belleville springs, etc. to simulate different stiffness and installation conditions. A total of 64 tests were performed. Analysis of the results shows that the preload mean is affected by torque, axiality, bolt diameter and plating while the preload dispersion is related to installation method, lubricant, plating and diameter. The exploratory nature of the study must be taken into account when interpreting the results. Also, a duplicate series of tests is being funded by the BTC to confirm the present findings.

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1. THE ENGINEERING PROBLEM OF PRELOAD IN BOLTING

The problem of preload response in bolting technology is a complex phenomenon. In a document prepared for the Bolting Technology Council, Bickford (1987) lists a set of 54 parameters (factors) which affect the torque/tension (preload) relationship of a joint fastened together with threaded products. This information is shown in the Ishikawa diagram of Fig. 1.

Following a request for proposal by the Bolting Technology Council, the authors were awarded a contract to study the problem with a statistically designed experimental approach. This is an exploratory study whose objective is to screen, among the many factors identified above, the active factors from the inert ones.

A brainstorming session held in Montreal with A. Craig Hood, identified a subset of 11 critical factors together with their respective low and high values in order to carry out a two-level screening experiment. The 11 factors selected are listed in Table 1 and are also printed in bold letters in Fig. 1.

2. DESIGNED EXPERIMENTS

2.1 Screening designs

The theory and practice of statistically designed experiments is a vital and important subject for engineers, scientists and experimenters. In the last decade, there has been a tremendous growth of designed experiments, particularly in industry. Since 1983, for example, there is an annual symposium on Taguchi methods (experimental designs) for quality engineering.

From a practical point of view, the steps in designing exploratory screening experiments are straightforward. These are based on so-called Plackett-Burman designs also known as Hadamard matrix designs, 2^{k-p} fractional factorial designs, or Taguchi orthogonal arrays, see Wheeler (1988). These designs are based on a small number of runs suitably chosen, see Fig. 2 and Table 2.

These designs have many interesting properties and characteristics such as:

- A large number of factors may be investigated with a minimum of runs; r factors can be studied in (r + 1) runs (saturated designs); for example, 127 factors can be screened in 128 runs;

- Each main effect is estimated independently of all other main effects and each is estimated with the same precision; this is related to the orthogonal property of the design;

- Main effects can be estimated and isolated from two-factor interactions by combining the basic design with its complementary (reflected or fold-over) design;

- The factors for which it is the hardest to change the levels are taken into account making it easier to carry out the experiment;

- The basic designs (geometric designs) have a number of runs r equal to a power of 2,

  $$r = 8, 16, 32, 64, 128.$$

  Note: Higher values of r are not used unless the study involves many hundreds of factors.

- There are also some intermediate designs (non-geometric) such as:

  $$r = 12, 20, 24, 28, 36, 38, 44, 46, 48, 60, 68, 69, 71, 72, 80, 81, 84, 93, 143.$$

In a geometric design (i.e. r = 8, 16, 32 ... runs) there is a unique correspondence between an interaction and a main effect. For non-geometric designs (r = 12, 20, 24,...) the confounding pattern is complex and is of little use in isolating individual effects. For this reason, the non-geometric designs are less informative in a sequential research program. However, since the gaps between geometric designs get progressively larger, some of the larger non-geometric designs can be useful as the first of a sequence of experiments. Unless the number of factors is large (more than 20, say) and the resources are scarce, it is preferable to use a geometric design.

A very important concept in the design of experiments is that of the Design Resolution as listed in Table 3. From a practical point of view, designs of resolution III and IV are the most useful for screening exploratory studies. It is also very easy to go from resolution III to resolution IV by folding over the basic design (i.e. using a reflected design, see below).

2.2 Designs for 11 factors

In our case, with 11 factors, a fully crossed experiment would require 2^{11} = 2048 runs. In such an experiment, all effects would be estimable:

11 main effects
55 two-factor interactions (first-order interactions)
1981 higher order interactions

In an exploratory study, we are not interested in high order interactions. In general, there are only a few active factors and many inert factors giving very few, if any, significant high order interactions. Moreover, time and/or cost considerations preclude even thinking of running an experiment with several thousand runs.

The alternate route is to opt for a fractional design approach in order to screen the active factors from the inert ones. Once this first stage experiment has been analyzed and if there is a need to estimate all of the effects, a full fractional experiment can then be performed on the active factors only.

From a practical point, the correct fractional factorial for screening purposes must be selected. In order to provide an answer to this question, the experimenter needs only to specify the design resolution. As a general rule, a resolution III design is a good starting point and, if necessary, can be augmented to reach a resolution IV design. Rarely is there a need to go to resolution V design in exploratory studies. Table 4 gives a set of candidate experimental designs for screening 11 factors.

2.3 Our experimental strategy

The following criteria have been retained for studying the selected 11 factors:

a) Simplicity of confounding pattern of main effects and interaction effects
b) Possibility of reaching resolution IV
c) Repeatability of results and analyses
d) Possibility of analyzing location measures and dispersion measures
e) Least number of runs
f) Sequential approach

Considering all of the above criteria, we have decided to:

- Start with the basic 16-run design since it is the smallest geometric design for 11 factors

- Combine the 16-run basic design with the reflected 16-run design to obtain resolution IV

- Replicate both the basic and reflected 16-run designs in order to satisfy criteria c) and d).

The details of each stage are given in Table 5.

3. THE SELECTED EXPERIMENTAL DESIGNS

3.1 Factor assignment for the basic 16-run design

Table 6 lists the 11 factors together with their low and high levels and their contrast label (letters A to O). Note that the 16-run design can accommodate up to 15 factors, one for each label A, B,..,O. In our case we have 11 factors and the labels I, J, L, O are not associated with any factors. These labels are used in the statistical analysis computations and they estimate pure interaction effects (Table 9).

3.2 The basic 16 run design

The basic 16-run design is outlined in Table 7. The high and low levels are indicated by + and - respectively. Note that the experiment is made easier by assigning the first, or leftmost contrast labels to those factors for which it is hardest to change levels. As an indication, the number of changes in level is also given in Table 7.

3.3 The reflected 16-run design

The reflected design is detailed in Table 8. Note that it is identical to Table 7 except that all signs have been inverted.

3.4 Confounding Patterns of Contrast

Table 9 lists the confounding patterns of contrast for the basic and reflected designs. Contrast label A, for example, estimates [A - BC -DE - FG] in the basic plan while in the reflected plan it estimates [A + BC + DE + FG]. Single letters indicate a main effects while double letters indicate an interaction. Note that each interaction is associated with a single contrast label.

Details on the statistical definitions and procedures are given in Appendices A, B, and C.

4. EXPERIMENTAL CONSIDERATIONS

Details of the experimental rig are given in Appendix D. It was specially designed for this experiment and consisted of two similar fixtures (one for the 3/8" fasteners, the other for the 3/4").

A stack of steel blocks, solid washers and Belleville springs, and a load transducer make up a fixture. The different components may be readily interchanged for the appropriate run. The head of the bolt fits in appropriate slots at the base of the fixture which is itself fastened to a heavy steel mount. This allows the operator to work unassisted during the torquing operation.

Appendix D also discusses the way in which the high and low values of each of the test parameters were achieved together with specific comments. All of the tests were performed by the same operator, see Nadeau (1989).

5. DATA ANALYSIS AND DISCUSSION

The experimental results are given in Apendix A (Tables 10 and 11). The statistical approach is detailed in Apendices B and C. In order to illustrate the trends, a number of graphs and summary tables are given in Figs. 2 to 7. Following are some details and discussion:

5.1 Central Tendency: Main Effects

Figure 2 shows the effect of each parameter taken individually. The table at the top of the figure lists the parameters in their order of importance while a schematic graphical representation is given at the bottom of the figure. While the overall mean value of pre-load is 62 ksi, torque, for example, affects it by +/-31.6 ksi. The positive slope on the graph indicates that the high or "+" value of torque produces a high value of pre-load. In the case of axiality, on the contrary, the high or "+" value is a 5° bevel which produces a lower torque value; so here the pre-load range is 62 -/+ 18.8 ksi and the slope of the schematic line is negative.

The fact that Torque, Axiality, and Diameter are the three parameters with the greatest effect on pre-load is not too surprising. Plating, which comes fourth in line, influences surface finish and surface lubricity and its effect on pre-load is reasonable. Next in line come Number of tightenings, Grade of fastener, Installation method and Lubricant with almost the same effect each. In the case of the Lubricant, it should be noted that the "unlubricated" bolts were not cleaned before the test but were actually used in the "as-received" condition (i.e. they were probably covered with a light protective layer of oil). Surprisingly, Corrosion, Joint stiffness, and Thread engagement are found to have an almost negligible influence on pre-load.

5.2 Central Tendency: Interactions

Figure 3 lists, in their order of influence on pre-load, the different groups of interactions. The following pairs appear to be the best candidates for interaction effects:

CH: Plating	and	Axiality
HN: Axiality	and	Diameter
KN: Torque	and	Diameter
CE: Plating	and	Grade

The interactions are suggested by the factors having a significant main effect.

5.3 Dispersion: Main Effects

Figure 5 shows the dispersion in pre-load due to the parameters taken individually. The presentation is very similar to that of Fig. 2. The parameter which most influences dispersion is, as expected, the Method of Installation (i.e. hand vs impact wrench); as discussed in Appendix D, the impact wrench, in particular, was very difficult to adjust and did not give repeatable torque values. However, the revealing aspect is that Lubricant is next in line with regards to dispersion; considering its small influence on the central tendency, this would seem to indicate that the lubricant contributes little to the level of pre-load while producing more scatter. Plating also produces dispersion but it was also seen to affect the central tendency as well. The effect of the other factors on dispertion is relatively less pronouced; of interest is the fact that Torque produces the least dispersion.

5.4 Dispersion: Interactions

As indicated in Fig. 6, the interpretation is not straightforward but possible important interactions are:

HN:	Axiality	and	Diameter
AC:	Corrosion	and	Plating
BC:	Lubricant	and	Plating
BN:	Lubricant	and	Diameter

6. CONCLUSIONS

6.1 A Summary of the Factors Importance

This invetigation started with eleven (11) factors thought to affect the pre-load response in a bolted joint. By using a set of 32 runs in a controlled screening experiment with a well chosen statistical design, we have been able to identify a first set of factors affecting the mean value of the response (torque, axiality, diameter, and plating) and a second set of factors affecting the dispersion of the response (installation, lubricant, plating, diameter).

Furthermore, we are suggesting that the following interactions are important: plating-axiality, diameter-axiality, torque-diameter, lubricant-plating, and lubricant-diameter.

Figure 7 illustrates the set of active factors in a joint fastened together with threaded products.

6.2 Further developments

At its meeting of June 6, 1989, the members of the Bolting Technology Council voted unanimously to fund a repeat experiment so as to verify the data and observations reported here. Phase II of the project is presently in progress under the authors' supervision. Some important points regarding the new test scheme:

1. A new set of bolts (3/8 and 3/4" diameter) is to be secured from a different supplier.

2. Two different experiments will be designed, one for each bolt diameter. This will increase the number of tests which will increase the resolution thus separating main effects from interaction effects.

3. A calibrated torquemeter will be used so as to reduce the uncertainly due to applied torque. Note that the use of calibrated torquemeters could imply that there is no point in running the series with the impact wrench. The number of factors would thus be reduced by one (to 10). One of three choices is presently being considered:

    a) Work with 10 factors only, thus increasing the resolution especially with regards to the interaction effects.
    b) Run the impact wrench series anyway
    c) Select another factor

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With his vast experience in bolting technology, A. Craig Hood's guidance was essential to this project.
The tests were performed by Jacques Nadeau as part of his final year undergraduate project in Mechanical Engineering at Ecole Polytechnique, Montreal. Jacques also contributed to the design the test rig. His engineering and technical skills are hereby acknowledged.

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APPENDIX A
DEFINITIONS AND EXPERIMENTAL RESULTS

Tables 10 and 11 give the experimental values and their derived statistical parameters for the basic and reflected designs, respectively. The following definitions apply:

A, B, ..., N, O : variables (see Table 6)

NAD1, NAD2 : preload in lbs (two replicates)

Y1, Y2 : preload in ksi (two replicates)

Yj = NADj/77.5 if Diameter = 3/8
NADj/334.0 if Diameter = 3/4
with j = 1,2

Note - The constants 77.5 and 334.0 are 1000 times the tensile stress areas (in^2) for 3/8 and 3/4 diameter bolts, respectively.

YBAR = (Y1 + Y2)/2 : mean response

$S^2 = (Y1 - YBAR)^2/2 + (Y2 - YBAR)^2/2$

$= (Y1 - Y2)^2/2$: variance

$LOG(S^2)$: natural Log of variance

APPENDIX B
STATISTICAL MODELS FOR ANALYSIS

B.1 Basic design model for the mean value of preload

$$\bar{Y}_i^B = \beta_{oo} + \beta_A X_{Ai} + \beta_B X_{Bi} + \dots + \beta_N X_{Ni} + \beta_0 X_{0i} \qquad (1)$$

where

$\bar{Y}_i^B$: Mean preload response (from 2 replicates) for run i = 1, 2, ... , 16

Superscript B refers to "Basic design"

β_{oo} : overall effect

$X_{Ai}, \dots, X_{0i}$: columns (contrast labels) of the basic design for run i (see Table 10)

$\beta_A, \dots, \beta_0$: statistical parameters

The overall effect and the statistical parameters are <u>estimated</u> by:

$$\hat{\beta}_{oo} = \frac{1}{16} \sum_{i=1}^{16} \bar{Y}_i^B = \bar{\bar{Y}}^B$$

$$\hat{\beta}_A = \frac{1}{16} \sum_{i=1}^{16} X_{Ai} \bar{Y}_i^B$$

$$\hat{\beta}_B = \frac{1}{16} \sum_{i=1}^{16} X_{Bi} \bar{Y}_i^B \qquad (2)$$

$$\vdots$$

$$\hat{\beta}_0 = \frac{1}{16} \sum_{i=1}^{16} X_{0i} \bar{Y}_i^B$$

where the ^ notation denotes an estimate.

As indicated in Table 9,

$\hat{\beta}_A$ estimates [A - (BC + DE + FG)]/2

$\hat{\beta}_B$ estimates [B - (AC + DF + EG)]/2

$\hat{\beta}_0$ estimates [-(AN + BM + DK + GH)]/2 where A, B, ... , O are the main effects for factors A, B, ... , O, and BC, DE, ... are the interaction effects. The analysis of the variance equation is given by:

$$\sum_{i=1}^{16} (\bar{Y}_i^B - \bar{\bar{Y}}^B)^2 = 16 \, (\beta_A^2 + \beta_B^2 + \ldots + \beta_N^2 + \beta_O^2) \qquad (3)$$

Note that, because of the orthogonal nature of the design,

$$\sum_{i=1}^{16} X_{Ai}^2 = \sum_{i=1}^{16} X_{Bi}^2 = \ldots = \sum_{i=1}^{16} X_{Oi}^2 = 16$$

and

$$\sum_{i=1}^{16} X_{Ai} \, X_{Bi} = \ldots = \sum_{i=1}^{16} X_{Ni} \, X_{Oi} = 0$$

B.2. Reflected design model for the mean value

$$\bar{Y}^R = \gamma_{oo} + \gamma_A X_{Ai} + \gamma_B X_{Bi} + \ldots + \gamma_N X_{Ni} + \gamma_O X_{Oi} \qquad (4)$$

where

$\bar{Y}_i^R$: mean preload response (from 2 replicates) for run i = 1, 2, ... , 16

Superscript R refers to "Reflected design."

γ_{oo} : overall effect

$X_{Ai}, \ldots, X_{Oi}$: columns (contrast labels) of the reflected design for run i (See Table 11)

$\gamma_A, \ldots, \gamma_O$: statistical parameters

The overall effect and the statistical parameters are estimated by:

$$\hat{\gamma}_{oo} = \frac{1}{16} \sum_{i=1}^{16} \bar{Y}_i^R = \bar{\bar{Y}}^R$$

$$\hat{\gamma}_A = \frac{1}{16} \sum_{i=1}^{16} X_{Ai} \bar{Y}_i^R \tag{5}$$

$$\vdots$$

$$\hat{\gamma}_O = \frac{1}{16} \sum_{i=1}^{16} X_{Oi} \bar{Y}_i^R$$

and

$\hat{\gamma}_A$ estimates [A + (BC + DE + FG)]/2

$\hat{\gamma}_B$ estimates [B + (AC + DF + EG)]/2 (6)

. . .

$\hat{\gamma}_O$ estimates (AN + BM + DK + GH)/2

B.3 Main and Interaction Effects

By combining equations (2) and (6) we get, for the main effects,

$$A = \beta_A + \gamma_A$$
$$B = \beta_B + \gamma_B$$
$$\vdots \tag{7}$$
$$N = \beta_N + \gamma_N$$

While the interaction effects are given by:

$$BC + DE + FG = \gamma_A - \beta_A$$
$$AC + DF + EG = \gamma_B - \beta_B$$
$$\vdots \tag{8}$$
$$AN + BM + DK + GH = \gamma_O - \beta_O$$

B.4 Model for preload dispersion

To identify the active factors related to the dispersion of the preload we have performed a similar analysis for the log of the sample variance S^2:

$$\log S_i^2 = \beta_{oo} + \beta_A X_{Ai} + \beta_B X_{Bi} + \dots + \beta_N X_{Ni} + \beta_O X_{Oi} \qquad (9)$$

over the basic and reflected designs. Similar computations (Equations (2)...(8)) hold for the dispersion models. They are not given here.

APPENDIX C
ANOM CHART

Four main factors are retained for the central tendency: torque (K), axiality (H), diameter (N) and plating (C). We have therefore 16 subgroups of size 2 from the combined data of the basic and reflected design. The values are given in Fig. 4.

The analysis of means (ANOM) is a graphical technique for comparing several means. The comparison is made via a chart similar to an XBAR and R charts used in quality control. The details are given in Wheeler (1988).

The ANOM limits are computed from

$$\bar{\bar{Y}} \pm H_{\nu,\alpha,k} \; \frac{1}{\sqrt{n}} \; \frac{\bar{R}}{d_2^*} \qquad (10)$$

where

$\bar{\bar{Y}}$: is the overall mean or grand average

$H_{\nu,\alpha,k}$: constants obtained from Table D in Wheeler (1988, p. 238)

ν : degrees of freedom (Table B, Wheeler 1988, p. 234)

α : significance level (0.05 say)

k : number of subgroups

n : sample size of subgroups

$\bar{R}$: average range

d_2^* : constant depending on n for bias correction (Table B, Wheeler 1988, p. 234)

In our case:

$$\bar{\bar{Y}} = 62, \ \nu = 14, \ k = 16, \ n = 2, \ \bar{R} = 11.3, \ d_2^* = 1.15$$

A control chart for the range gives an Upper Control Limit for R (UCL_R):

$$UCL_R = D_4 \ \bar{R} = 3.27 \times 11.3 = 37.0$$

where D_4 is taken from Wheeler (1988) Table C, p. 236.

We see, for example that subgroup 1 (K = +, H = +, N = +, C = +) is out of control (Figure 4).

After eliminating subgroups 1, 5, 7 and 9 the remaining subgroups yield an average range $\bar{R} = 4.81$ with an Upper Control Limit for R:

$$UCL_R = D_4 \bar{R} = 3.27 \times 4.81 = 15.7$$

The contributing subgroups are all in control, so the unbiased estimate of the standard deviation for the pre-load is:

$$\hat{\sigma}_1 = \frac{\bar{R}}{d_2^*} = \frac{4.81}{1.1} = 4.4$$

This estimate is in agreement with the average value of the variance (S^2) of the basic and reflected designs:

$\bar{S^2}$ = 21.0 basic design

$\bar{S^2}$ = 17.1 reflected design

$$\bar{\sigma} = \left(\frac{21.0 + 17.1}{2}\right)^{1/2} = 4.4$$

The ANOM limits are computed from Equation (10):

$$\bar{\bar{Y}} = 62, \quad \nu = 14, \quad d_2^* = 1.15, \quad \bar{R} = 4.81,$$

$$n = 2, \quad \alpha = 0.05, \quad H_{\nu,\alpha,k} = 3.40$$

ANOM limits: $62 \pm 3.40 \frac{1}{\sqrt{2}} \frac{4.81}{1.15} = 62 \pm 10$

These limits are represented by the horizontal dashed lines in Fig. 4.

We note that of all the 16 subgroups defined by K, H, N and C only subgroups 3, 8, 9 are within the control limits (52 to 72). This indicates that they are not statistically different from each other.

APPENDIX D
EXPERIMENTAL DETAILS

This appendix is based on **Jacques Nadeau**'s (1989) Mechanical Engineering final year undergraduate project.

D.1. The Test Fixtures

Figure 8 shows the assembly drawing of a typical arrangement of one of the two fixtures built specifically for the present study. Each fixture is made up of the following groups of components:

a) The test fastener consisting of the bolt (item 4 in Fig. 8), the nut (10) and a solid washer (9). Most of these items were certified as indicated in Table 12. They were used only once in the test program.

b) A load cell (5) consisting of a short cylinder instrumented with strain gages in a full Wheatstone bridge arrangement. The load cell gives a combined strain reading which is only sensitive to axial load. Temperature variations, bending, and torsional effects are cancelled out. Each of the two load cells was calibrated on a precision hydraulic test machine. The gain of the bridge amplifier was adjusted so as to give a strain gage read-out in physical units of load (lbs).

c) The stack of plates or blocks representing the bolted joint (6, 7, 8, and 14). To satisfy the different test run requirements -- i.e. flexible vs rigid joint, straight vs misaligned (non-axial), full- vs half-thread engagement -- a number of different components were used:
   - A lower plate (6).
   - Parallel-faced or bevelled upper plates (7) of different thicknesses.
   - A solid washer or a stack of Belleville spring washers (8). The Belleville springs selected had an ID larger than the OD of the test bolts, so a guide (13) was used for proper alignment. Discussion on the choice and arrangement of the Belleville springs is given in Section D.2 below.

d) A gripping arrangement consisting of:
   - A pair of lower grips (2) bolted to the test bench (1) with a total of four bolts (12). These grips are machined and installed in such a way as to be clear of the load cell (5) while preventing the head of the test bolt (4) from rotating during the torquing operation.
   - A pair of upper grips (3) bolted to the lower grips (2) with a total of four bolts (11). These grips are designed to clamp the lower plate (6) of the test joint assembly.

   Note that the gripping arrangement is designed in such a way that, by releasing the clamping bolts (11), the test bolted assembly easily slides out.

e) A heavy test bench (1) bolted to the floor.

Typical photographs are given in Figs. 9 to 12: Figure 9 shows the full set of test fixture components before assembly. The 3/4" diameter solid joint is shown in Fig. 10. The 3/8" flexible joint with Belleville springs is shown in Fig. 11 while Fig. 12 shows a misaligned 3/8" solid joint.

D.2. Belleville Spring Arrangement

During the test fixture design phase, it was decided that the stiffness of the stack of Belleville springs should be about 50% of that of the test bolts, thus:

$$K_{bolt} = AE/L \qquad (11)$$

with A = cross-sectional area of bolt using nominal diameter
E = Modulus of elasticity = 30 x 10^6 psi
L = nominal bolt length = 5"

From equation (11) the stiffness of the 3/8" and 3/4" diameter bolts is computed as 2.78 x 10^6 and 10.6 x 10^6 lb/in respectively. So the required corresponding Belleville spring stiffnesses was: 1.39 x 10^6 and 5.3 x 10^6 lb/in respectively. Also, it was necessary that the springs be overdesigned so as not to compress them beyond their linear-elastic range.

On hand were a number of Belleville spring washers 2-1/4" OD x 1-3/8" ID x 3/8". Their stiffness was determined experimentally to be 2.8 x 10^6 lb/in and was thus well suited for our needs since, by using two such washers in either a series or a parallel arrangement (See Fig. 13), the following stiffnesses could be obtained:

$$K(\text{series}) = 2.8 \times 10^6 \ / \ 2 = 1.4 \times 10^6 \ \text{lb/in}$$

$$K(\text{parallel}) = 2.8 \times 10^6 \times 2 = 5.6 \times 10^6 \ \text{lb/in}$$

So, a pair of washers were used in series in the 3/8" fixture and another pair was used in parallel in the 3/4" one. Each of the two fixtures was provided with a special sleeve for holding the Belleville washers in a centered position (Item 13 in Fig. 8).

D.3 Test Parameters

Following are some specific details on the way the experimental factors listed in Table 6 were acheived. For each parameter, "low" and "high" values (or "-" and "+" levels) were defined.

D.3.1 Corrosion (Factor A)

Low value: No corrosion. The test fasteners were used in their "as-received" condition.

High value: As shown in Fig. 13 the test bolts were dipped in a solution containing 3.5% in weight of table salt in water. The bolts were immersed head down only up to one half of the anticipated thread engagement. Immersion time was 3 hours for the unplated bolts and 100 hours for the plated ones. The nuts and washers were not corroded.

D.3.2 Lubrication (Factor B)

Low value: No lubrication. The test fasteners were used in their "as-received" condition. They were not cleaned with solvents.

High value: A thin coating of Molybdenum-disulfite (Molykote by Alpha Corp.) was applied to the threaded end of the bolts.

Note that in the the design of the experiments, the first factors are those that are subject to the least number of changes (see Tables 7 and 8). This is an important point with regards to testing lubricated vs unlubricated bolts. Nevertheless, before testing unlubricated bolts, the fixtures were thoroughly cleaned and de-greased to prevent contamination.

D.3.3 Plating (Factor C)

Low value: Plain bolts, nuts and washers

High value: As indicated in Table 12, depending on their size and grade, the bolts, nuts and washers used were either zinc-yellow coated (Gr. 5 nad 8) or hot-dip galvanized (ASTM A-325 and a-490 bolts). The matching finish fasteners were always used as a group (nut, bolt, washer). See also D.3.5 below.

D.3.4 Tightenings (Factor D)

Low value: Full torque was applied once.

High value: Full torque was applied four times with an interval of about 5 seconds in between.

Note: During the early stages of the program, we considered the possibility of retorquing at increasing torque levels. This approach was found to be inconvenient, however, because it meant that the torque or impact wrenches, had to be reset after every tightening, resulting in loss of precision and repeatability. See also D.3.9 and D.3.10 below.

D.3.5 Grade (Factor E)
Low value: Grade 5 or A-325
High value: Grade 8

Note: As indicated in Table 12, in some cases we had to use a Grade A-563 nut with a Grade 8 bolt. In one case we used a Gr. A-563 nut with a Grade A-325 bolt. In all cases the washers were of the hardened type. The zinc-yellow chromate nuts had no lot numbers. All of the washers were hardened and tempered.

D.3.6 Stiffness of joint (Factor F)
Low value: With Belleville spring washers (see Section D.2 above), Fig. 11.
High value: With solid blocks, Fig. 10.

D.3.7 Thread Engagement (Factor G)
Low value: Full thread engagement, Fig. 15.
High value: Half thread engagement, referring to the threads in the nut as shown in Fig. 15.

D.3.8 Axiality (Factor H)
Low value: No misalignment.
High value: 5° of misalignment, using a wedged block as shown in Fig. 13. Note that the angle of 5° applies to the upper face of the wedged block. The hole was drilled to a diameter large enough to provide clearance as the bolt bends during tightening.

D.3.9 Torque (Factor K)
Low value: 50% of recommended seating torque (see below).
High value: 75% of recommended seating torque.
Originally the high value was set to be 100% of the recommended seating torque but this caused stripping of the threads when the fasteners were either corroded or assembled with half thread engagement. As a compromise, we set the high value to 75% of full torque.

Recommended Seating Troques (From Table 13)	Low 50%	High 75%
3/8"-16, Gr. 5 .... T = 38 ft-lb.	16	24
3/8"-16, Gr. 8 ....T = 50 ft-lb.	25	38
3/4"-10, A-325 ....T = 300 ft-lb.	150	225
3/4"-10, Gr. 8 ....T = 425 ft-lb.	213	319

D.3.10 Installation Method (Factor M)
Low value: With a torque-wrench.
Wrenches used: - "Norbar" SL1, capacity 6 to 40 ft-lbs ("click" type)
- "Snap-on," capacity 0-1000 ft-lbs ("dial" type).

High value: With an impact wrench.
Wrenches used: - CP 734 air wrench, 1/2"-drive, capacity 25 to 280 ft-lbs
- CP 772 air wrench, 3/4"-drive, (capacity rating unavailable)

In order to attain the required torque values with the impact wrenches with some degree of precision it was necessary to maintain a good control on each of the following:

- Pressure of air supply (from 50 to 100 psig).
- Wrench throttle valve position (arbitrary graduations, from 0 to 15 for small wrench, and from 0 to 9 for large one).
- Duration of torquing operation (from 2 to 22 seconds).

Through a series of trials involving practise fasteners, the level of each of the above was adjusted until the preload reading was about the same as that obtained by the respective torque wrenches. This turned out to be a tedious and difficult operation producing a large scatter in torque levels for the same set of parameters.

D.3.11 Diameter of Bolt (Factor N)
Low value: 3/8" - 16
High value: 3/4" - 10

Refer to Table 12 for details.

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TABLE 1
SELECTED FACTORS

Corrosion	(3.5% salt solution)
Lubricant	(MOS2)
Plating	(Chromate dip)
Tightenings	(Up to 4 repeats)
Grade of bolt	(Grades 5 and 8)
Stiffness of joint	
Thread engagement	(Half and full)
Axiality	(Up to 5-degree bevel washer)
Torque level	
Installation method	(Hand and impact wrench)
Diameter of bolt	(3/8 and 3/4 inch)

TABLE 2
NUMBER OF FACTORS AS A FUNCTION
OF NUMBER OF TRIALS AND DESIGN RESOLUTION

NUMBER OF TRIALS	DESIGN RESOLUTION			
	V^+	V	IV	III
6			3	
8	3		4	5-7
12		4	5-6	8-11
16	4	5	7-8	12-15
20				16-19
24			9-12	20-23
32	5	6	13-16	24-31
36				32-35
44				36-43
48		7-8	17-24	44-47
60				48-59
64	6		25-32	60-63
68				64-67
72				68-71
80				72-79
84				80-83
96		9-11	33-48	
128	7		49-64	84-127

Ref. Diamond (1981), p.190

TABLE 3
LEVELS OF DESIGN RESOLUTION

DESIGN RESOLUTION	MEANING
II	main effects confounded with other main effects
III	main effects are unconfounded but there is confounding of two-factor interactions with main effects
IV	main effects unconfounded with other main effects but some interactions are confounded with other interactions
V	main effects and two-factors unconfounded (all can be estimated)
V+	all main effects and all interactions of all orders can be estimated (fully crossed experiment)

TABLE 4
SOME FRACTIONAL AND OTHER FACTORIAL DESIGNS
FOR SCREENING 11 FACTORS
(assuming all interactions above first order to be negligible)

DESIGN ID	FRACTION OF 2048 RUNS	NUMBER OF RUNS	RESO-LUTION	NUMBER OF ESTIMATED 2-FACTOR INTERACTIONS (first order)*
1	1/16	128	V	55
2	1/32	64	IV	31
3	1/64	32	IV	15
4	1/128	16	III	4
5	not a fraction	12	III	0
6	not a fraction	20	III	8
7	not a fraction	24	III	12

* Free of main effects

TABLE 5
EXPERIMENTAL STRATEGY

STAGE	DESIGN	RESPONSE VALUES	STATISTICAL ANALYSIS
1	Basic 16-run design	y_i,1: value at run i stage 1 i = 1, 2,...,16	-Contrast estimates -Anova table -Scree diagram -Conclusions
2	Basic 16-run design (replication)	y_i,2: value at run i stage 2 i = 1, 2,...,16	-Contrast estimates -Anova table -Scree diagram -Conclusions
3	---	---	Comparaison of statistical analysis of stage 1 and stage 2 (repeatability)
4	---	$\bar{y}_i^{B} = \frac{(y_{i,1} + y_{i,2})^2}{2}$ i = 1,2,...,16	-Contrast estimates -Anova table -Scree diagram -Conclusions
5 (optional)	---	$S_i^{2,B} = \frac{(y_{i,1} - y_{i,2})^2}{2}$ On log scale i = 1,2,...,16	-Contrast estimates -Anova table -Scree diagram -Conclusions
6	Reflected 16-run design	y_i,6: value at run i stage 6 i = 1, 2,...,16	-Contrast estimates -Anova table -Scree diagram -Conclusions

cont'd

TABLE 5 (CONT'D)
EXPERIMENTAL STRATEGY

STAGE	DESIGN	RESPONSE VALUES	STATISTICAL ANALYSIS
7	reflected 16-run design (replication)	$y_{i,7}$: value at run i stage 7 $i = 1, 2, \ldots, 16$	-Contrast estimates -Anova table -Scree diagram -Conclusions
8	---	---	Comparaison of statistical analysis of stage 6 and stage 7 (repeatability)
9	---	$\bar{y}_i^{R} = \frac{y_{i,6} + y_{i,7}}{2}$ $i = 1,2,\ldots,16$	-Contrast estimates -Anova table -Scree diagram -Conclusions
10 (optional)	---	$S_i^{2,B} = \frac{(y_{i,6} - y_{i,7})^2}{2}$ On log scale $i = 1,2,\ldots,16$	-Contrast estimates -Anova table -Scree diagram -Conclusions
11	---	$\bar{y}_i^{B}, \bar{y}_i^{R}$ $i = 1,2,\ldots 16$	-Separating main effects and interactions -Identification of active factors
12 (optional)	This stage is necessary if it is essential to estimate higher order interactions. Do a full factorial experiment of those active factors identified at stage 11. For example, if 5 of the 11 factors are active, a full factorial experiment would require 32 runs.		

TABLE 6
THE SELECTED EXPERIMENTAL FACTORS

LETTER	FACTOR NAME	LOW LEVEL (-)	HIGH LEVEL (+)
A	Corrosion	as is	3.5% salt solution
B	Lubricant	clean	MOS2
C	Plating	as is	chromate dip
D	Tightenings	1	4
E	Grade of bolt	grade 5	grade 8
F	Stiffness of joint	belleville spring	solid washer
G	Thread engagement	half	full
H	Axiality	0 degree	5 degrees
I			
J			
K	Torque	50% of table*	75% of table*
L			
M	Installation method	hand wrench	impact wrench
N	Diameter of bolt	3/8 inch	3/4 inch
O			

* See Table 13

TABLE 7
THE BASIC 16-RUN DESIGN

run no.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Contrast Labels														
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+
3	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-
4	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+
5	-	+	+	+	+	-	-	-	-	+	+	+	+	-	-
6	-	+	+	+	+	-	-	+	+	-	-	-	-	+	+
7	-	+	+	-	-	+	+	+	+	-	-	+	+	-	-
8	-	+	+	-	-	+	+	-	-	+	+	-	-	+	+
9	+	+	-	-	+	+	-	-	+	+	-	-	+	+	-
10	+	+	-	-	+	+	-	+	-	-	+	+	-	-	+
11	+	+	-	+	-	-	+	+	-	-	+	-	+	+	-
12	+	+	-	+	-	-	+	-	+	+	-	+	-	-	+
13	+	-	+	+	-	+	-	-	+	-	+	+	-	+	-
14	+	-	+	+	-	+	-	+	-	+	-	-	+	-	+
15	+	-	+	-	+	-	+	+	-	+	-	+	-	+	-
16	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

Treatment combinations are defined by rows in this matrix.

Contrast coefficients are defined by columns in this matrix.

Number of changes in level

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Ref.: Wheeler (1989), p.40

TABLE 8
THE REFLECTED 16-RUN DESIGN

run no.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-
3	+	+	+	-	-	-	-	-	-	-	-	+	+	+	+
4	+	+	+	-	-	-	-	+	+	+	+	-	-	-	-
5	+	-	-	-	-	+	+	+	+	-	-	-	-	+	+
6	+	-	-	-	-	+	+	-	-	+	+	+	+	-	-
7	+	-	-	+	+	-	-	-	-	+	+	-	-	+	+
8	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
9	-	-	+	+	-	-	+	+	-	-	+	+	-	-	+
10	-	-	+	+	-	-	+	-	+	+	-	-	+	+	-
11	-	-	+	-	+	+	-	-	+	+	-	+	-	-	+
12	-	-	+	-	+	+	-	+	-	-	+	-	+	+	-
13	-	+	-	-	+	-	+	+	-	+	-	-	+	-	+
14	-	+	-	-	+	-	+	-	+	-	+	+	-	+	-
15	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+
16	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

Treatment combinations are defined by rows in this matrix.

Contrast coefficients are defined by columns in this matrix.

Number of changes in level

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

TABLE 9
CONFOUNDING PATTERNS OF CONTRASTS
BASIC PLAN

Labels of contrasts:	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Main effects:	A	B	C	D	E	F	G	H			K		M	N	
Interactions: (55)	-BC -DE -FG	-AC -DF -EG	-AB -DG -EF -HK -MN	-AE -BF -CG	-AD -BG -CF -HM -KN	-AG -BD -CE -HN -KM	-AF -BE -CD	-CK -EM -FN	-AH -BK -DM -GN	-AK -BH -DN -GM	-CH -EN -FM	-AM -BN -DH -GK	-CN -EH -FK	-CM -EK -FH	-AN -BM -DK -GH

REFLECTED PLAN

Labels of contrasts:	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Main effects:	A	B	C	D	E	F	G	H			K		M	N	
Interactions: (55)	BC DE FG	AC DF EG	AB DG EF HK MN	AE BF CG	AD BG CF HM KN	AG BD CE HN KM	AF BE CD	CK EM FN	AH BK DM GN	AK BH DN GM	CH EN FM	AM BN DH GK	CN EH FK	CM EK FH	AN BM DK GH

Ref.: Wheeler (1989), p.45

TABLE 10
DATA FOR RUNS 1-16
BASIC PLAN WITH 2 REPLICATES

A. CONTRAST LABELS

OBS	RUN	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	2	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
3	3	-1	-1	-1	1	1	1	1	1	1	1	1	-1	-1	-1	-1
4	4	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1
5	5	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1
6	6	-1	1	1	1	1	-1	-1	1	1	-1	-1	-1	-1	1	1
7	7	-1	1	1	-1	-1	1	1	1	1	-1	-1	1	1	-1	-1
8	8	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1
9	9	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1
10	10	1	1	-1	-1	1	1	-1	1	-1	-1	1	1	-1	-1	1
11	11	1	1	-1	1	-1	-1	1	1	-1	-1	1	-1	1	1	-1
12	12	1	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1
13	13	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1
14	14	1	-1	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	1
15	15	1	-1	1	-1	1	-1	1	1	-1	1	-1	1	-1	1	-1
16	16	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1

B. RESULTS

RUN	DIAM	NAD1	NAD2	Y1	Y2	YBAR	S^2Y	$LOG(S^2)$
1	3/8	1970	2070	25.419	26.710	26.065	0.832	-0.1834
2	3/4	21200	23800	63.473	71.257	67.365	30.299	3.4111
3	3/8	6030	5790	77.806	74.710	76.258	4.795	1.5676
4	3/4	24400	23850	73.054	71.407	72.231	1.356	0.3044
5	3/8	7830	7410	101.032	95.613	98.323	14.685	2.6868
6	3/4	20250	21100	60.629	63.174	61.901	3.238	1.1750
7	3/8	1350	1310	17.419	16.903	17.161	0.133	-2.0159
8	3/4	41100	40850	123.054	122.305	122.680	0.280	-1.2725
9	3/4	24400	24250	73.054	72.605	72.829	0.101	-2.2942
10	3/8	5760	5750	74.323	74.194	74.258	0.008	-4.7885
11	3/4	26050	27200	77.994	81.437	79.716	5.928	1.7796
12	3/8	2000	2020	25.806	26.065	25.935	0.033	-3.4022
13	3/4	32450	32150	97.156	96.257	96.707	0.403	-0.9079
14	3/8	1940	2640	25.032	34.065	29.548	40.791	3.7085
15	3/4	9350	9050	27.994	27.096	27.545	0.403	-0.9079
16	3/8	5030	6460	64.903	83.355	74.129	170.231	5.1372

TABLE 11
DATA FOR RUNS 17-32
REFLECTED PLAN WITH 2 REPLICATES

A. CONTRAST LABELS

OBS	RUN	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	18	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
3	19	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1
4	20	1	1	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1
5	21	1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1
6	22	1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1
7	23	1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	-1	1	1
8	24	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1
9	25	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1
10	26	-1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1
11	27	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1
12	28	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	1	-1
13	29	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
14	30	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
15	31	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
16	32	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1

B. RESULTS

RUN	DIAM	NAD1	NAD2	Y1	Y2	YBAR	S^2Y	$LOG(S^2)$
17	3/4	29850	33500	89.3713	100.299	94.8353	59.7122	4.0895
18	3/8	4210	3910	54.3226	50.452	52.3871	7.4922	2.0139
19	3/4	24850	29300	74.4012	87.725	81.0629	88.7559	4.4859
20	3/8	4700	4870	60.6452	62.839	61.7419	2.4058	0.8779
21	3/4	10600	8300	31.7365	24.850	28.2934	23.7101	3.1659
22	3/8	4930	5530	63.6129	71.355	67.4839	29.9688	3.4002
23	3/4	26900	28600	80.5389	85.629	83.0838	12.9531	2.5613
24	3/8	3880	3540	50.0645	45.677	47.8710	9.6233	2.2642
25	3/8	4150	4120	53.5484	53.161	53.3548	0.0749	-2.5913
26	3/4	30650	27800	91.7665	83.234	87.5000	36.4055	3.5947
27	3/8	3750	3050	48.3871	39.355	43.8710	40.7908	3.7085
28	3/4	19450	18150	58.2335	54.341	56.2874	7.5747	2.0248
29	3/8	2790	2600	36.0000	33.548	34.7742	3.0052	1.1003
30	3/4	23850	25000	71.4072	74.850	73.1287	5.9275	1.7796
31	3/8	4690	4900	60.5161	63.226	61.8710	3.6712	1.3005
32	3/4	8500	9450	25.4491	28.293	26.8713	4.0451	1.3975

TABLE 12
FASTENER COMBINATIONS

SIZE AND CONDITION	BOLT - GRADE (NOTE 1)	NUT - GRADE	WASHER
3/8" - 16			
PLAIN	SAE J429 GR 5	SAE J995C GR 5	HARD
ZINC YELLOW CHROMATE, 0.0002"	SAE J429 GR 5	(NOTE 2)	HARD
PLAIN	SAE J429 GR 8	SAE J995C GR 8	HARD
ZINC YELLOW CHROMATE, 0.0002"	SAE J429 GR 8	(NOTE 2)	HARD
3/4" - 10			
PLAIN	ASTM A-325	ASTM A-325	HARD
HOT DIP GALVANIZED	ASTM A-325	ASTM A-563 DH	HARD
PLAIN	SAE J429 GR 8	ASTM A-563 DH	HARD
ZINC YELLOW CHROMATE, 0.0002"	SAE J429 GR 8	(NOTE 2)	HARD

NOTES:
(1) BOLTS WERE 5" LONG
(2) NO LOT NUMBERS PROVIDED

TABLE 14 -

LOAD CARRYING CAPACITIES AND RECOMMENDED SEATING TORQUES *

For DRY Assembly of Plain Finish

Cleveland Hexagon Head Cap Screws

NOTE: **Surface finish must be taken into consideration. Variables such as lubrication, plating, etc., on either the screw or the mating surface may vary the torque values listed by as much as 20%.**

Nom. Dia. of Cap Screws Thd/in.	Tensile Stress Area (Sq. In.) [1]	Grade 2			Grade 5			Grade 8		
		Proof Load Min. (Lbs.)	Tensile Strength Min. (Lbs.)	Recomm. Torque (Ft - Lbs) 2, 1	Proof Load Min. (Lbs.)	Tensile Strength Min. (Lbs.)	Recomm. Torque (Ft - Lbs) 1	Proof Load Min. (Lbs.)	Tensile Strength Min. (Lbs.)	Recomm. Torque (Ft - Lbs) 1
Coarse Thread - UNC										
1/4-20	0.0318	1750	2350	6	2700	3800	11	3800	4750	12
5/16-18	0.0524	2900	3900	13	4450	6300	21	6300	7850	25
3/8-16	0.0775	4250	5750	23	6600	9300	38	9300	11600	50
7/16-14	0.1063	5850	7850	37	9050	12800	55	12800	15900	85
1/2-13	0.1419	7800	10500	57	12100	17000	85	17000	21300	125
9/16-12	0.182	10000	13500	82	15500	21800	125	21800	27300	175
5/8-11	0.226	12400	16700	111	19200	27100	175	27100	33900	245
3/4-10	0.334	18400	24700	200	28400	40100	300	40100	50100	425
7/8-9	0.462	15200	27700	185	39300	55400	450	55400	69300	660
1"-8	0.606	20000	36400	280	51500	72700	680	72700	90960	990
1-1/8-7	0.763	25200	45800	400	56600	80100	885	91600	114400	1470
1-1/4-7	0.969	32000	58100	565	71700	101700	1255	116300	145400	2100
1-3/8-6	1.155	38100	69300	740	85500	121300	1635	138600	173200	2750
1-1/2-6	1.405	46400	84300	985	104000	147500	2180	168600	210800	3640
Fine Thread - UNF										
1/4-28	0.0364	2000	2700	7	3100	4350	13	4350	5450	15
5/16-24	0.0580	3200	4330	14	4900	6950	23	6950	8700	30
3/8-24	0.0878	4800	6500	26	7450	10500	40	10500	13200	60
7/16-20	0.1187	6550	8800	41	10100	14200	60	14200	17800	95
1/2-20	0.1599	8800	11800	64	13600	19200	95	19200	24000	140
9/16-18	0.203	11200	15000	91	17300	24400	140	24400	30400	195
5/8-18	0.256	14100	18900	128	21800	30700	210	30700	38400	270
3/4-16	0.373	20500	27600	223	31700	44800	330	44800	56000	460
7/8-14	0.509	16800	30500	205	43300	61100	490	61100	76400	700
1"-12	0.663	21900	39800	310	56400	79600	715	79600	99400	1050
1"-14	0.679	22400	40700	315	57700	81500	715	81500	101900	1050
1-1/8-12	0.856	28200	51400	445	63300	89900	990	102900	128400	1655
1-1/4-12	1.073	35400	64400	625	79400	112700	1380	128800	161000	2310
1-3/8-12	1.315	43400	78900	845	97300	138100	1875	157800	197200	3110
1-1/2-12	1.3	52200	94900	1105	117000	166000	2430	189700	237200	4110

1. Stress Area for thread sizes
   $A = 0.7854\ (D - 0.9743/N)^2$
   A = Area; D = Nominal Diameter
   N = Threads/Inch

2. General Formula used to calculate seating torque

$$\text{Torque (ft. lbs.)} = \left[\frac{0.2 \times \text{Nominal Dia. of Screw}}{12}\right] \times \left[\text{Preload Lbs.}\right]$$

* Industrial Products Divison, SPS Technologies
4444 Lee Rd., Cleveland, OH. 44128

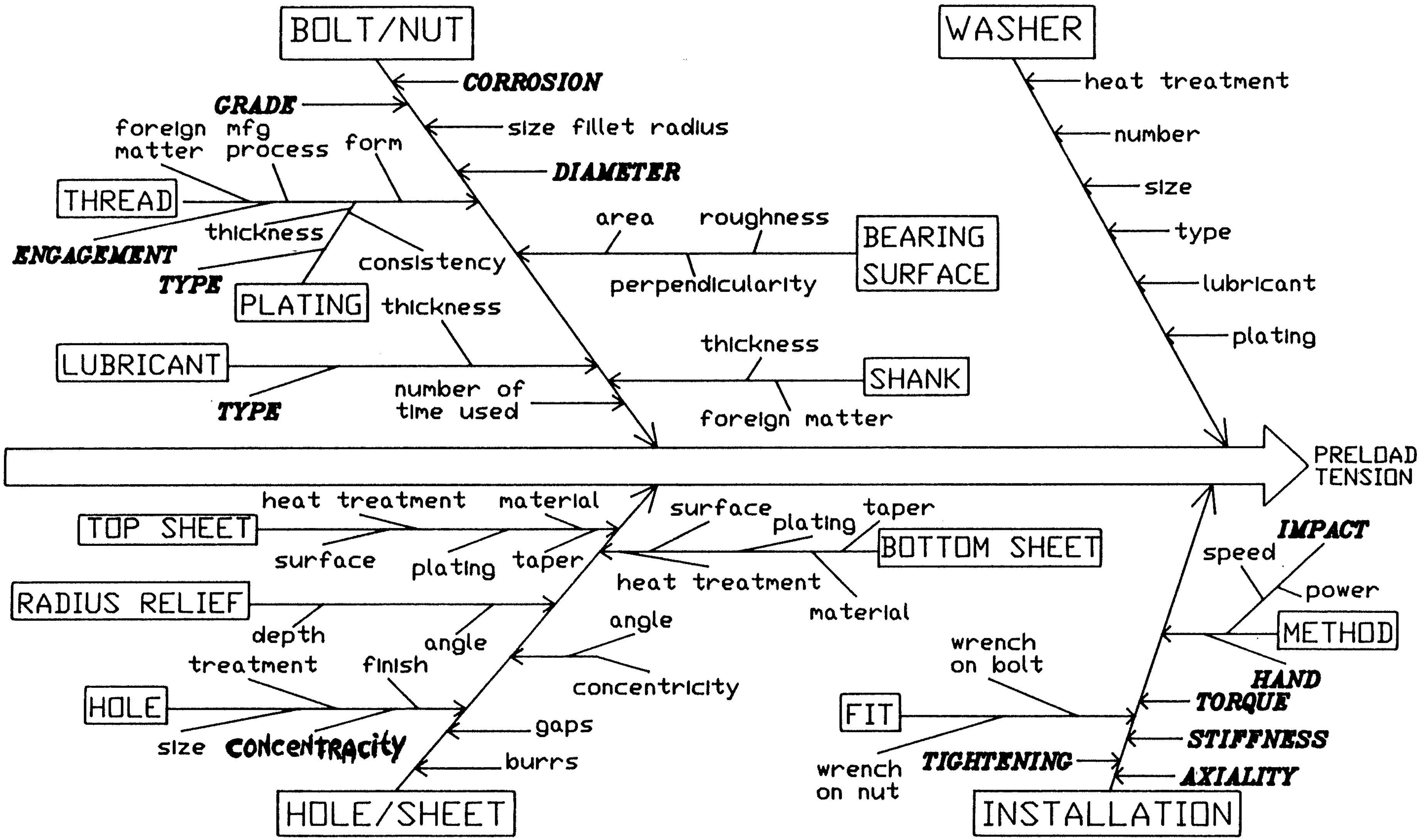


Fig. 1 Ishikawa diagram: Causes and effect

DATA ANALYSIS

CENTRAL TENDENCY

DATA : BASE PLAN + REFLECTED PLAN

MAIN EFFECTS

FACTOR	EFFECT	FACTOR	EFFECT
K: Torque	31.58	D: Tightening	7.48
H: Axiality	-18.84	E: Grade	6.89
N: Diameter	17.93	M: Installation	6.81
C: Plating	8.81	B: Lubricant	6.37
		A: Corrosion	1.11
		F: Stiffness	0.63
		G: Thread	-0.14

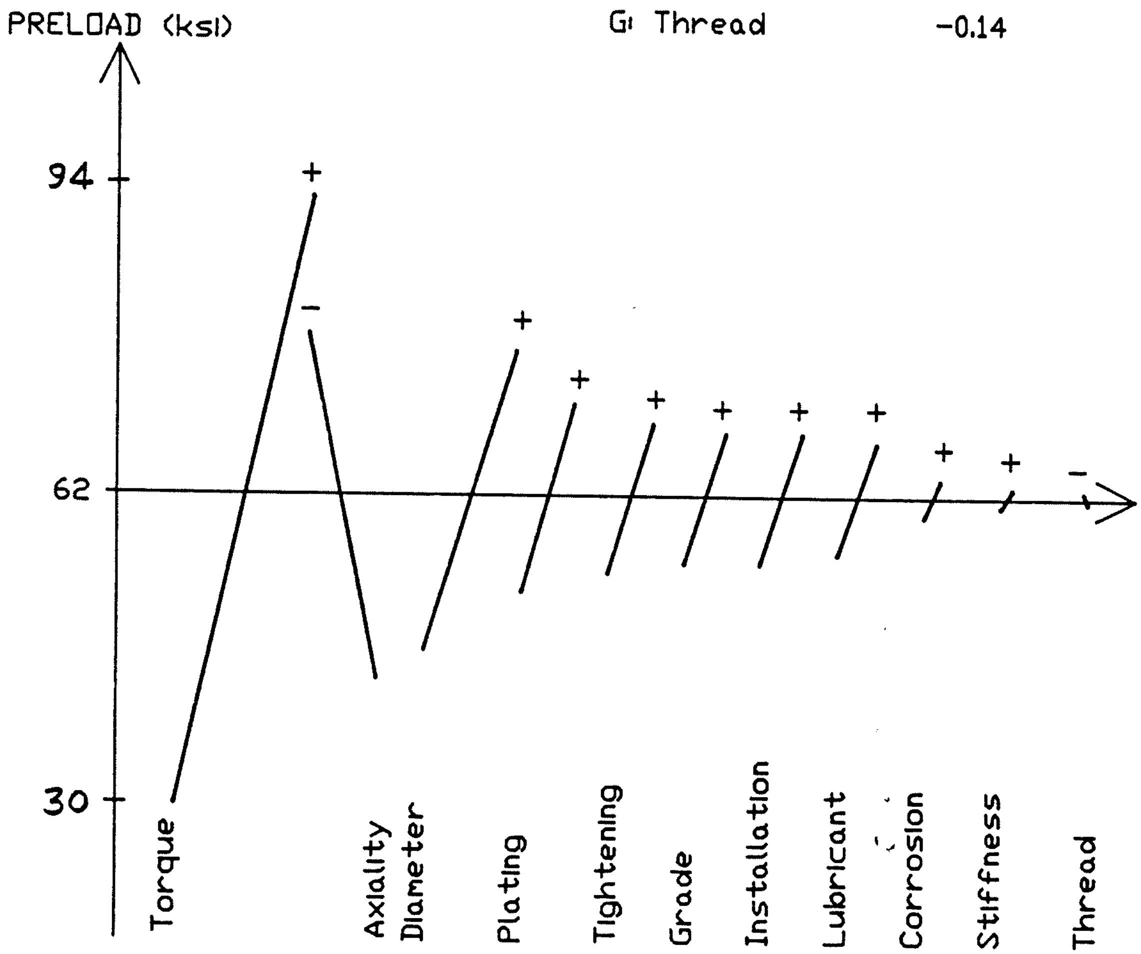


Fig. 2 Data analysis: main effects for central tendency

DATA ANALYSIS

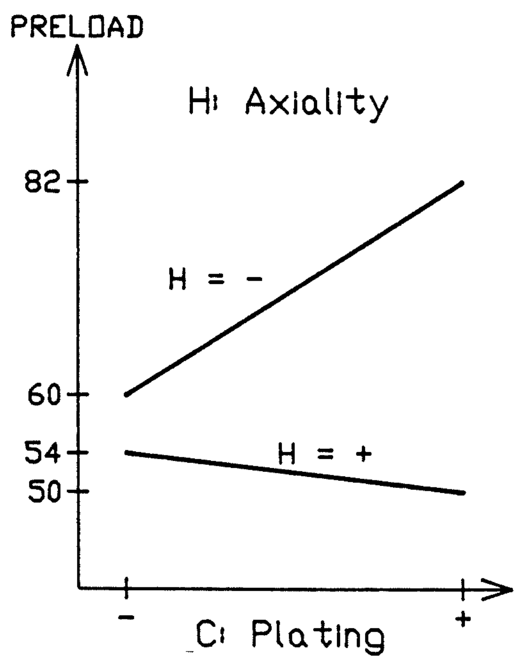
CENTRAL TENDENCY

DATA : BASE PLAN + REFLECTED PLAN

INTERACTIONS

PARAMETER	EFFECT	PARAMETER	EFFECT
CH+EN+FM	-12.94	CM+EK+FH	-4.47
AG+BD+CE+HN+KN	-11.96	AC+DF+EG	-4.00
BC+DE+FG	8.78	AF+BE+CD	3.78
CN+EH+FK	6.81	J: AK+BH+DN+GM	1.72
I: AH+BK+DM+GN	5.12	O: AN+BM+DK+GH	-1.60
AB+DG+EF+HK+MN	4.64	L: AM+BN+DH+GK	1.07
AD+BG+CF+HM+KN	-4.63	CK+EM+FN	0.55
		AE+DG+CG	0.16

Possibilities : CH, HN, KN, CE



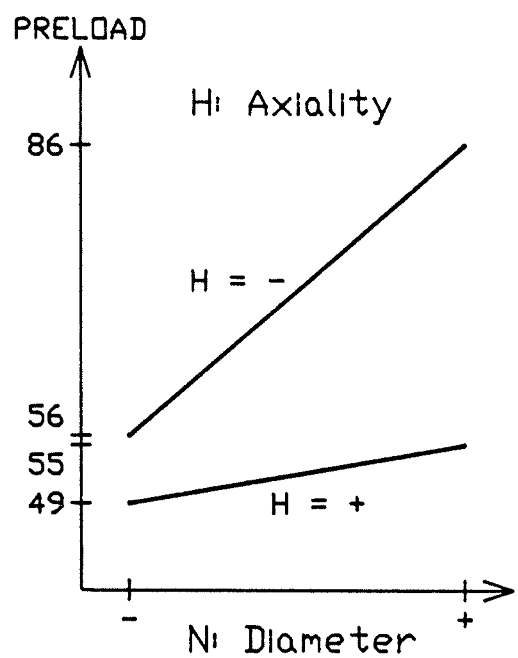


Fig. 3 Data analysis: interaction effects, central tend.

ANOM CHART

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TORQUE	K	+	+	+	+	+	+	+	+	−	−	−	−	−	−	−	−
AXIALITY	H	+	+	+	+	−	−	−	−	+	+	+	+	−	−	−	−
DIAMETER	N	+	+	−	−	+	+	−	−	+	+	−	−	+	+	−	−
PLATING	C	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−
Values of Preload		94.8 56.3	79.7 67.4	61.7 53.4	76.3 74.3	122.7 96.7	83.1 73.1	98.3 74.1	67.5 61.9	61.9 27.5	28.3 26.9	17.2 24.5	47.9 34.8	87.5 81.1	72.8 72.2	52.4 43.9	26.1 25.9
Meanvalues		75.5	73.5	57.5	75.3	109.7	78.1	86.2	64.7	64.7	27.6	23.3	41.4	84.3	72.5	48.1	26.0
Range		38.5	12.3	8.3	2.0	26.0	10.0	24.2	5.6	34.4	1.4	12.3	13.1	6.4	0.6	8.5	0.1

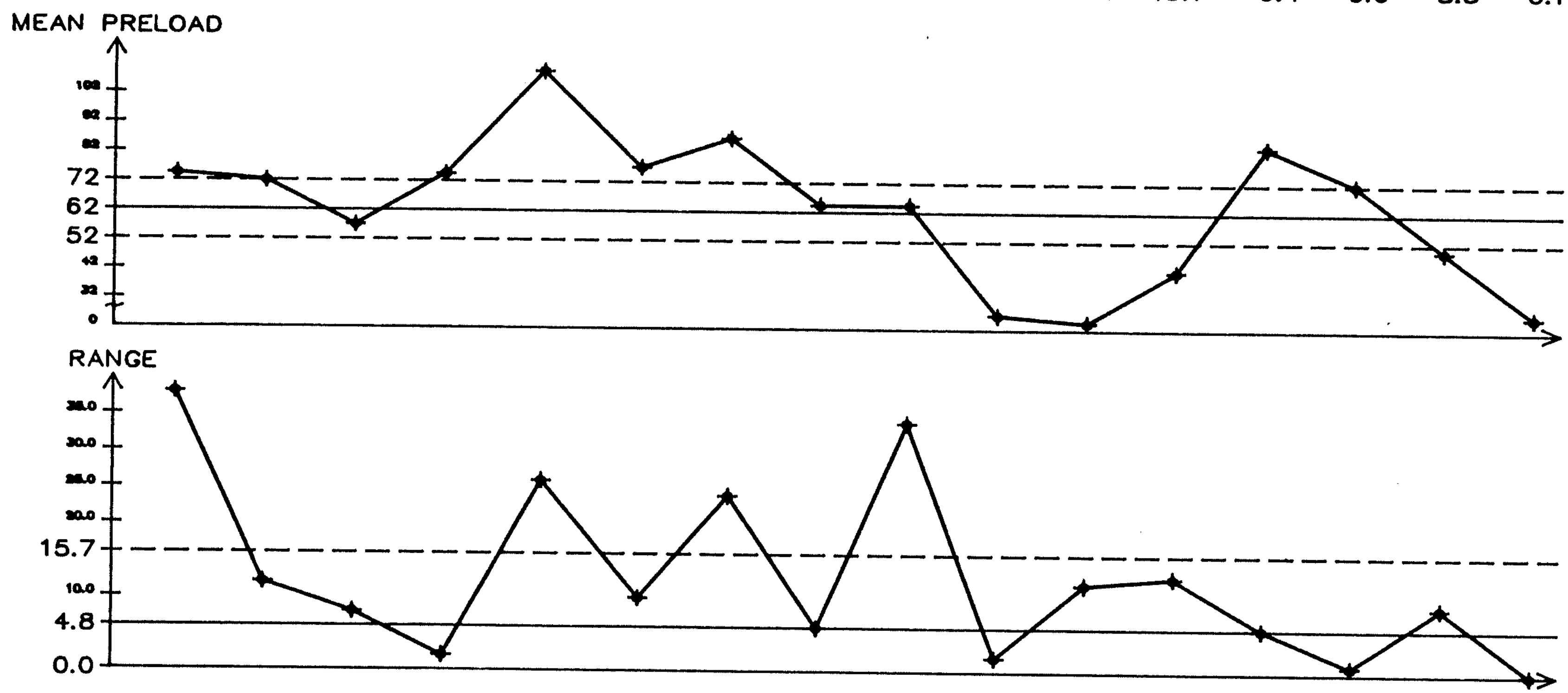


Fig. 4 ANOM Chart

DATA ANALYSIS

DISPERSION : $LOG(S^2)$

DATA : BASE PLAN + REFLECTED PLAN

MAIN EFFECTS

FACTOR	EFFECT
M: Installation	1.93
B: Lubricant	1.33
C: Plating	0.79
N: Diameter	0.60

FACTOR	EFFECT
F: Stiffness	−0.52
H: Axiality	−0.42
E: Grade	0.36
D: Tightening	0.25
G: Thread	−0.23
A: Corrosion	0.20
K: Torque	0.18

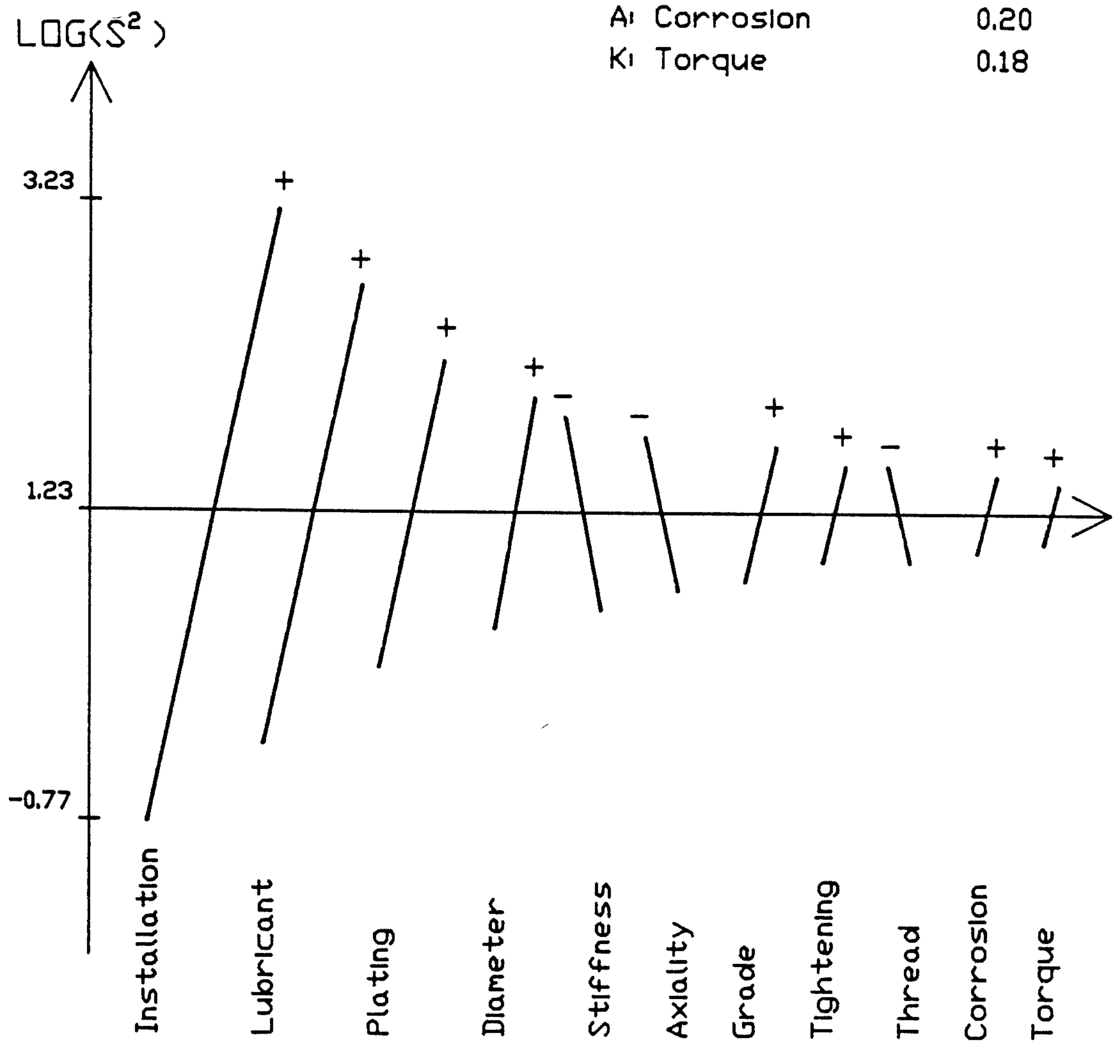


Fig. 5 Data analysis: main effects for dispersion

DATA ANALYSIS

DISPERSION : $LOG(S^2)$

DATA : BASE PLAN + REFLECTED PLAN

INTERACTIONS

PARAMETER	EFFECT	PARAMETER	EFFECT
AG+BD+CE+HN+KM	1.40	CM+EK+FH	0.78
AC+DF+EG	-1.20	CM+EK+FH	-0.76
BC+DE+FG	1.12	AB+DG+EF+HK+MN	-0.64
AM+BN+DH+GK	1.07	I: AH+BK+DM+GN	0.32
AE+DG+CG	-0.99	O: AN+BM+DK+GH	-0.26
CK+EM+FN	-0.90	J: AK+BH+DN+GM	0.21
CH+EN+FM	-0.86	AD+BG+CF+HM+KN	0.14
		AF+BE+CD	-0.03

Possibilities : HN, AC, BC, BN

Fig. 6 Data analysis: interaction effects, dispersion

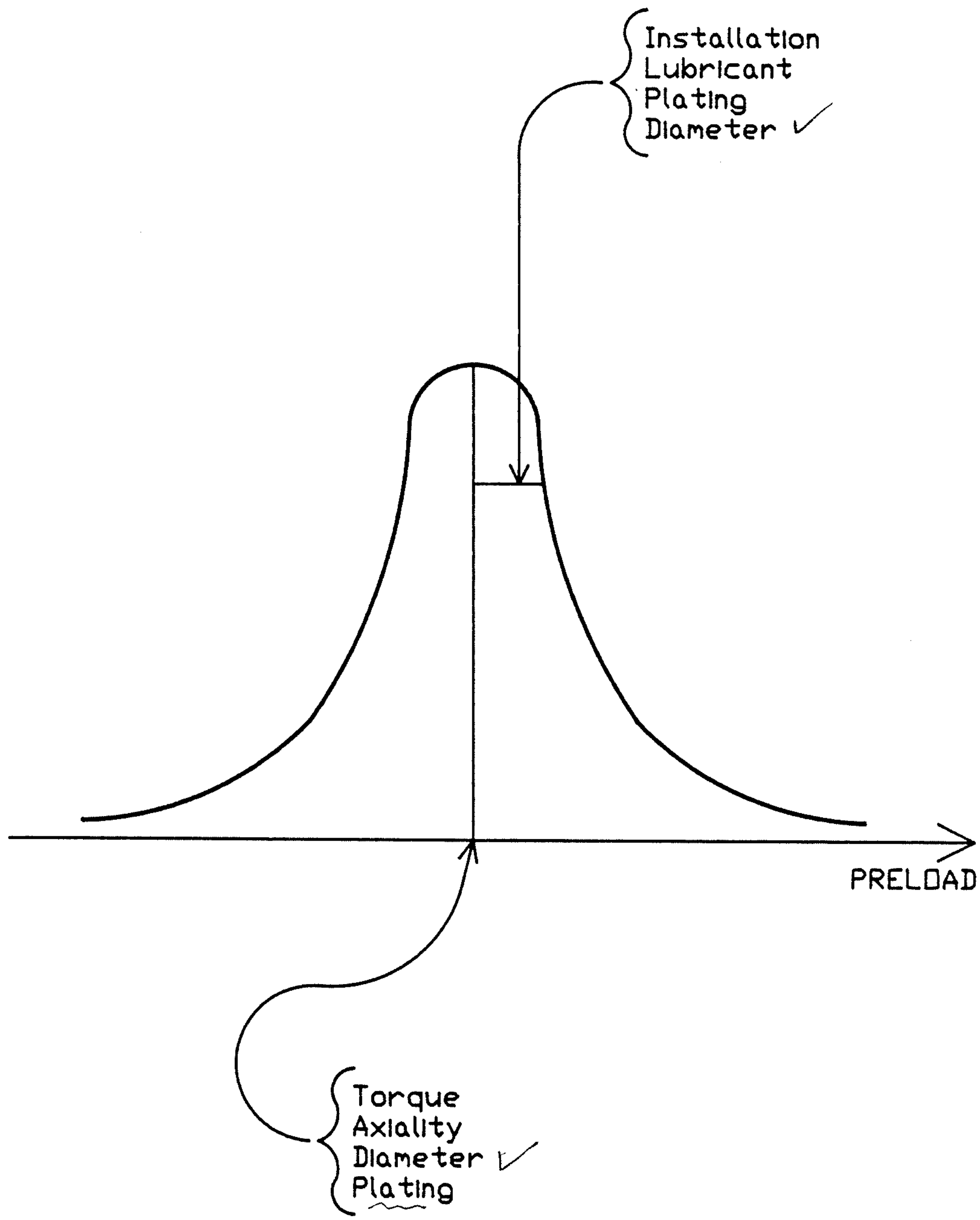
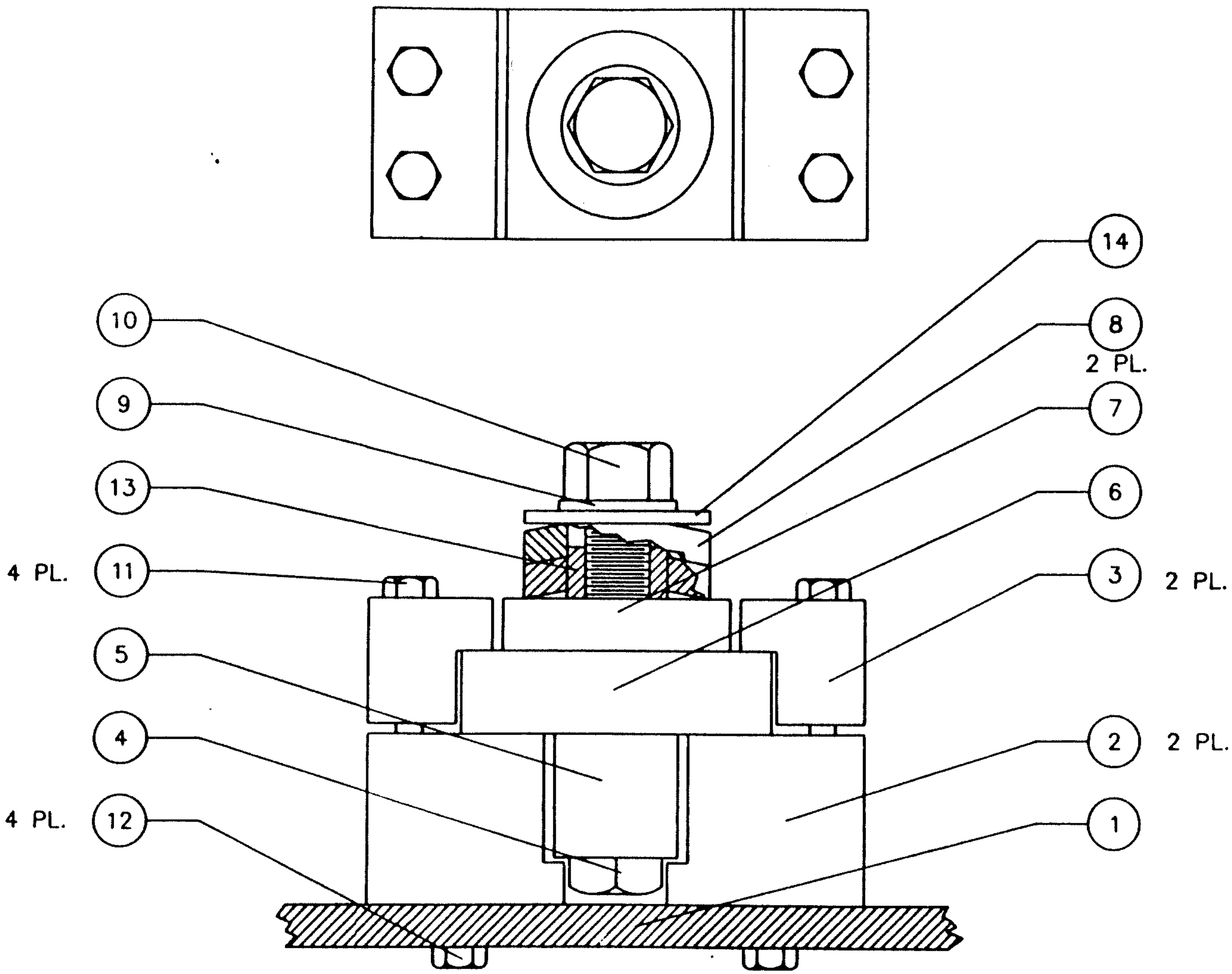


Fig. 7 Factors affecting central tendency and dispersion



Note: For more rigid assembly, springs (8) are replaced by solid washers.

No	DESCRIPTION	QTY	MAT.
1	table	1	———
2	lower grip	2	steel
3	upper grip	2	steel
4	test bolt	1	std
5	force transducer	1	steel
6	lower block	1	steel
7	upper block	1	steel
8	Bellevilles Springs	2	std
9	test washer	1	std
10	test nut	1	std
11	holding bolts	4	std
12	holding bolts	4	std
13	Bellevilles springs guide	1	steel
14	solid ring	1	steel

ECOLE POLYTECHNIQUE
DE MONTREAL

titre PRELOAD EVALUATION TEST ASSEMBLY WITH BELLEVILLES SPRINGS

dessine par Jacques Nadeau	dessin no ASS-2

echelle ———	date 89/01/18	feuille 1 de 1

Fig. 8 Typical assembly drawing of text fixtures

FICHIER : ASS-2. DWG

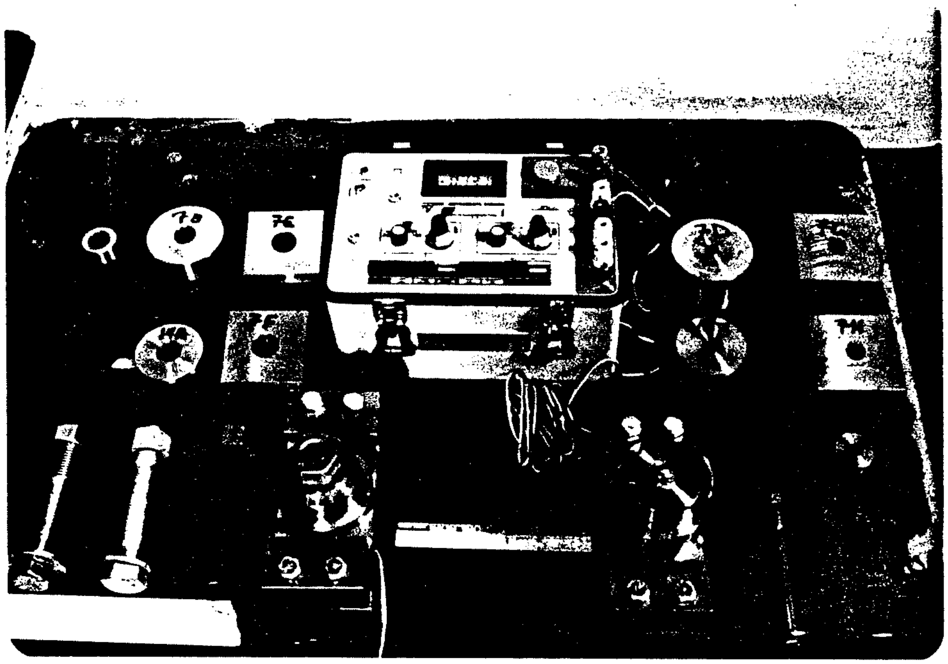


Fig. 9 The two test fixtures with strain indicator, additional components and test fasteners

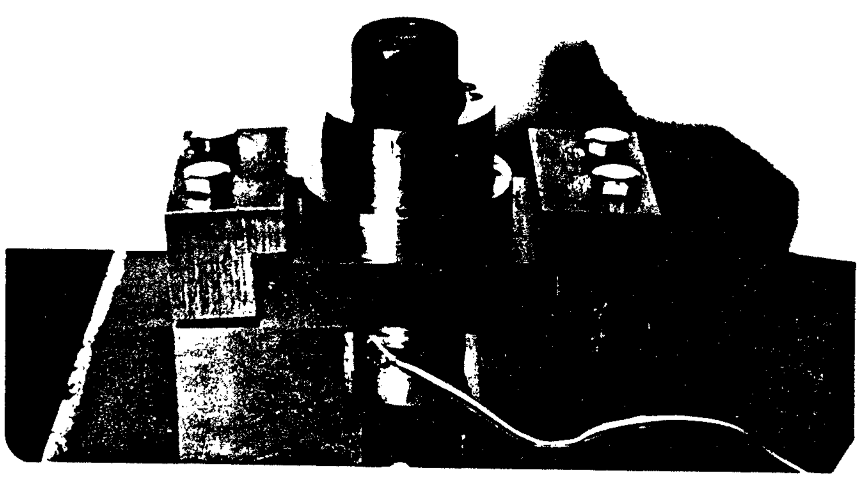


Fig. 10 The 3/4" fixture with rigid washer

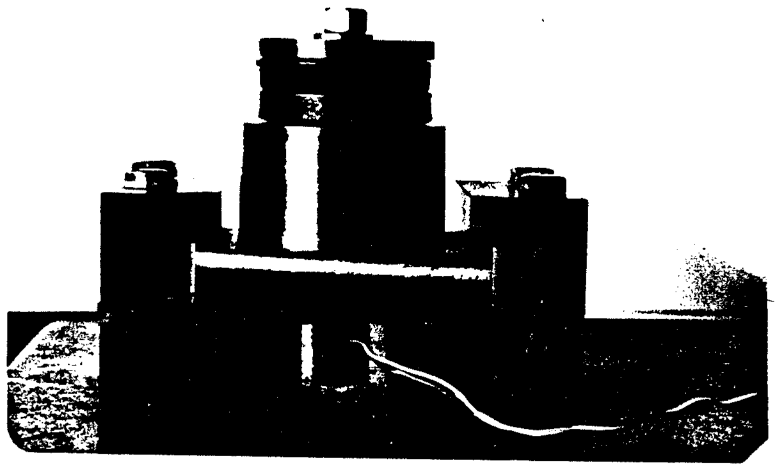


Fig. 11 The 3/8" fixture with with Belleville washers in series

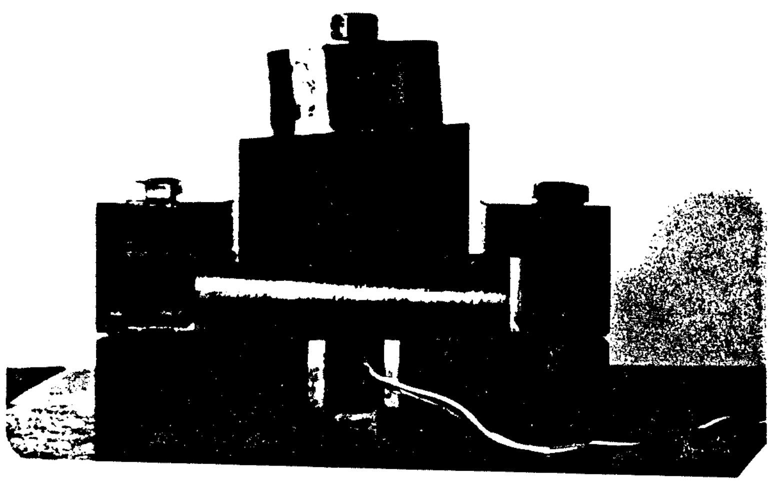


Fig. 12 The 3/8" fixture with wedged upper block

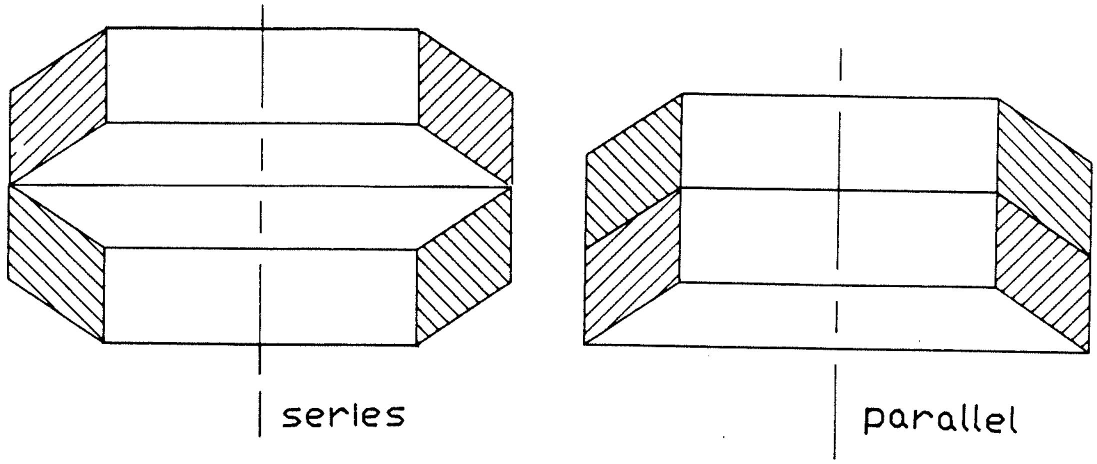


Fig. 13 Belleville springs in series and in parallel

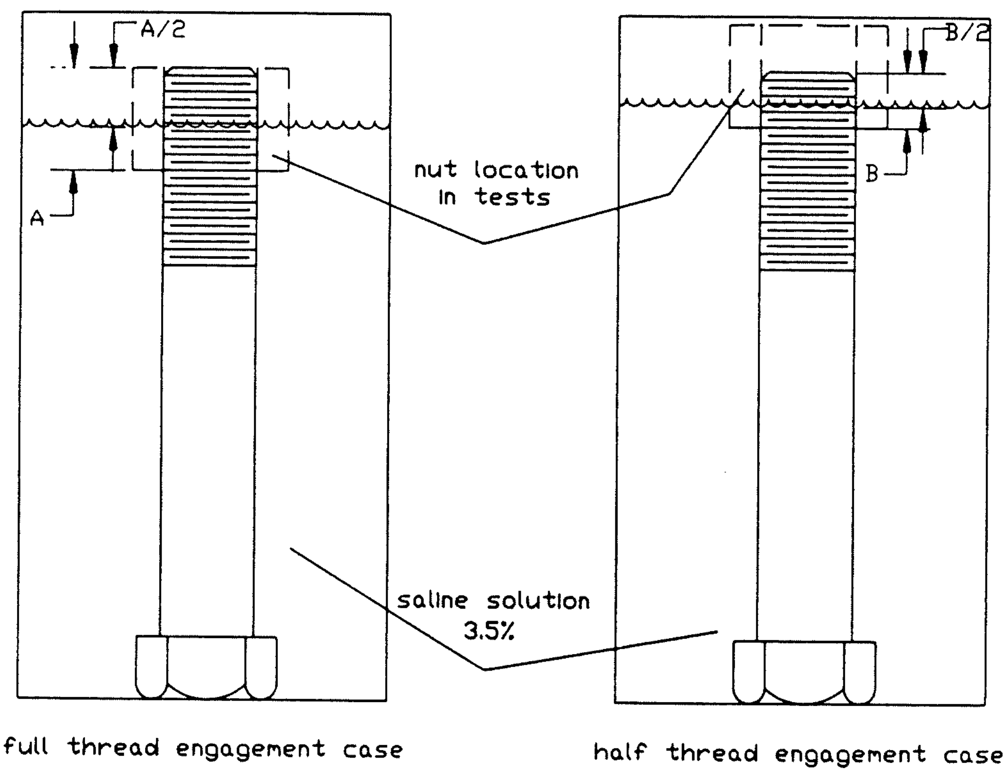


Fig. 14 Extent of immersion of bolt in saline solution for corrosion series

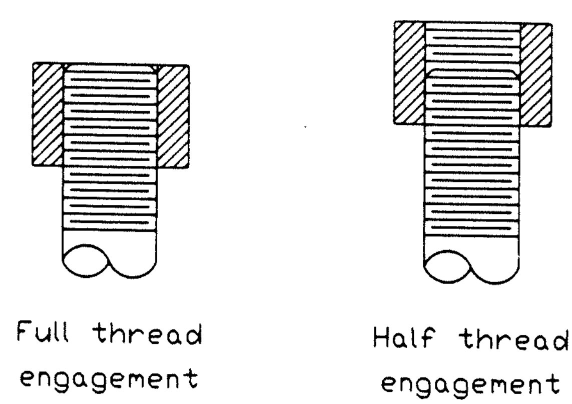


Fig. 15 Full vs half thread engagement