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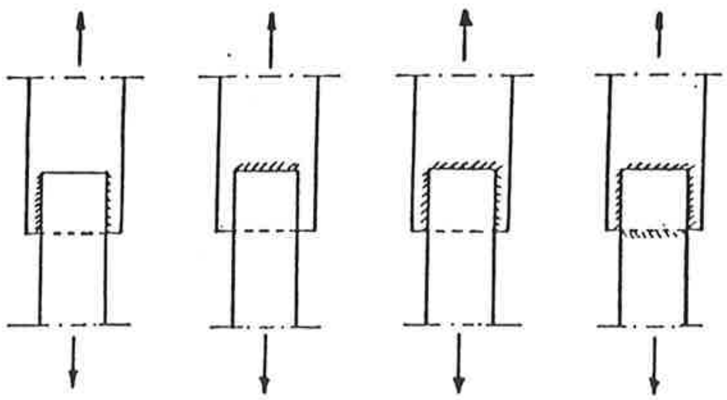
Report No.: BI-88-139

EVALUATION OF TEST RESULTS ON WELDED CONNECTIONS IN ORDER TO OBTAIN STRENGTH FUNCTIONS AND SUITABLE MODEL FACTORS - PART A: RESULTS



BI-88-139 EVALUATION OF TEST RESULTS ON WELDED CONNECTIONS IN ORDER TO OBTAIN STRENGTH FUNCTIONS AND SUITABLE MODEL FACTORS - PART A: RESULTS

October 1988
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Background report to Eurocode 3 "Common unified rules for steel structures"

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CONTENTS OF PART A: RESULTS PAGE

CONTENTS OF PART B: EVALUATIONS

ABSTRACT

On European level work is going on to come to harmonisation of design procedures for steel structures in the form of common unified rules in Eurocode No. 3. The Eurocode is presented in a limit state design (LFRD) format. In this report background information is presented on the strength functions and model factors for welded connections, given in Eurocode No. 3 (EC 3).

In order to arrive at strength functions and suitable model factors for welded connections, a statistical re-evaluation of available test results has been carried out.

The following procedure has been used for the determination of the design rules on welds in the 1988 revision of EC 3. Based on observation of actual behaviour in tests and on theoretical considerations a "design model" is selected. Then by statistical interpretation of all available test data i.e. regression analysis, the efficiency of the model is checked. Eventually the design model has to be adapted until the correlation of the theoretical values and the test data is sufficient. Then through manipulation with the statistical data of the test population, the model factor γ_M can be determined. Dividing the strength function by the model factor γ_M gives the design expression.

Starting points for the strength functions for welded connections are the functions presented in [1]. The results of the statistical analyses of the available test data of these connections are presented. Eventually, strength functions and model factors included in the 1988 revision of Eurocode No. 3 are determined.

The report has been split up into two parts:

- Part A: Results;
- Part B: Evaluations.

NOTATION

a	=	the throat size of a weld
a_1, a_2	=	constants
A	=	throat area, $A = a\ell$
A_1	=	throat area for welds perpendicular to the loading direction, $A_1 = ab$
A_2	=	throat area for welds parallel to the loading direction, $A_2 = a\ell$
b	=	the weld length
$\bar{b}$	=	mean value correction
f_u	=	specified ultimate tensile strength of plate material
$f_{u,w}$	=	the ultimate tensile strength of the fillet weld
$f_{u,wm}$	=	the ultimate tensile strength of the weld metal
f_y	=	the yield stress of the plate material
F	=	the force due to design loads
F_i	=	the theoretical resistance of the weld
k	=	a parameter in the strength function for fillet welds
k_d	=	fractile factor for a 75% predicting probability
k_s	=	fractile factor for estimating 5% fractiles
ℓ	=	the weld length
n	=	number of welds
r_n, r_k, r_d	=	nominal, characteristic and design resistance
r_{ei}	=	experimental resistance for specimen i
t_{ti}	=	theoretical resistance obtained by using the strength function for specimen i
R_k	=	characteristic resistance factor, 5% fractile
R_d	=	design resistance factor
t	=	plate thickness
V	=	coefficient of variation
V_δ	=	coefficient of variation of observed error terms
β	=	reliability index or coefficient in the strength function for fillet welds
β_w	=	the efficiency coefficient of a fillet weld
γ_M	=	model factor (partial safety factor) related to the 5% fractile
γ_M^*	=	modified model factor $\gamma_M^* = \gamma_M\ \Delta K$
ΔK	=	ratio between nominal and characteristic resistance: $\Delta K = r_n/r_k$

σ_w = the mean stress on the throat section of a weld

$\sigma_\perp$ = the tensile or compressive stress acting perpendicularly to the throat section

$\sigma_{/\!/}$ = the tensile or compressive stress acting parallel to the weld axis on the cross section of the weld

τ_u = the ultimatie shear strength of the parent metal

$\tau_{u,w}$ = the ultimate shear strength of the weld

$\tau_\perp$ = the shear stress acting perpendicularly to the weld axis, lying in the throat section

$\tau_{/\!/}$ = the shear stress acting parallel to the weld axis, lying in the throat section

|| — ⊓ □ are symbols referring to weld configurations; see e.g. figure 5.3 or table I.1.1.

Note:
The values for γ_M, ΔK and γ_M^* as defined here, result from the evaluation procedure [3]: $\gamma_M^* = \gamma_M \, \Delta K$. The γ_M^*-values are harmonised into one γ_M^o-value which, for convenience, is represented by γ_M in codes and in the parts A and B of this report.

1. INTRODUCTION

In this report the theoretical background to the strength functions for welded connections as presented in the 1988 revision of Eurocode No. 3 is provided. These strength functions are based upon a theoretical model which is explained briefly. The strength functions are compared with experimental data. Experimental data on welded connections are summarized in [2]. Based upon these experimental data a statistical evaluation of the strength functions is carried out which is described in detail in [3]. The statistical evaluation results in an update of the strength function considered. This new strength function is included in the 1988 revision of Eurocode 3.

In chapter 2 the procedure to arrive at strength functions and appropriate model factors is presented briefly. In chapter 3 the basic assumptions of parameters used are given such as materials used, reliability index, etc. In chapter 4 the failure mechanism for welded connections is mentioned. In chapter 5 the procedure to arrive at appropriate strength functions and model factors is applied to the failure mechanism for welded connections. Finally in chapter 6, the conclusions and the strength functions for welded connections are summarized.

This evaluation project is a common effort of:
- TNO Institute for Building Materials and Structures (IBBC-TNO);
- Eindhoven University of Technology (TUE);
- Aachen University of Technology (RWTH).

Test results have been considered as given in [7 to 13]. Only test results given in [7 to 9] have actually been used in the statistical evaluations.

2. PROCEDURE TO ARRIVE AT STRENGTH FUNCTIONS AND MODEL FACTORS

First of all the strength function for the failure mechanism considered is presented. The theoretical model on which the strength function is based is explained briefly. Background information is provided on the failure mechanism and on the model that describes this failure mechanism and so on the strength function used. The strength function as presented in [1] is reformatted. Then, a statistical evaluation [3] of the strength function with respect to the available experimental data [2] is carried out. This statistical analysis is reported in appendices. It is tried to end up with one single factor γ_M for the failure mechanism and strength functions considered: γ_M = 1.25. Therefore, the strength function has to be modified. The conclusions with respect to strength function and model factors are given here.

The statistical analyses reported in the appendices contain a definition of samples and subsamples referring to [2]. Furthermore in the appendices, plots are provided for samples and subsamples of test results r_{ei} versus results obtained by using the strength function r_{ti}. If necessary, sensitivity diagrams are provided for relevant parameters.

3. BASIC ASSUMPTIONS

In this chapter the basic assumptions used in the statistical evaluations are presented.

3.1 Plate material

In table 3.1 the plate materials and their design tensile strengths are given as used in the statistical evaluations.

Table 3.1: Plate material

steel grade	design tensile strength f_u (N/mm^2)
FeE235	360
FeE355	510

3.2 Reliability index

The reliability index used in the statistical evaluations is $\beta = 3.8$. See [3].

3.3 Coefficients of variation

From preknowledge the coefficients of variation used for the basic variables are estimated to be:

- tensile strength of plate material $V_{f_u} = 0.07$;
- throat area $V_A = 0.10$.

4. FAILURE MECHANISM FOR WELDED CONNECTIONS

Failure of components containing fillet welds may occur in the connected parts besides the weld, in the weld itself or partly in the weld and partly in the connected parts. For developing a strength function for fillet welds, it is clear that only those cases where weld failure governs are relevant.

The available calculation methods for checking the strength of fillet welds are all based upon the simplifying assumption that stresses are uniformly distributed within the throat section of a fillet weld. In EC 3 [1] two calculation methods are considered:

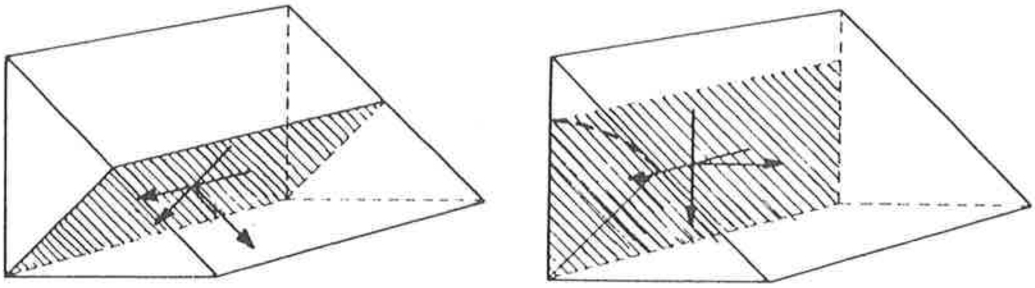
- method 1: stress component method;
- method 2: mean stress method.

Method 1, the stress component method, assumes the throat section in its actual position as the resisting section. The stress components on this throat section are calculated and used in the strength function. This method was proposed by IIW and approved by ISO in 1961.

In method 2, the mean stress method, an average stress on the throat section of a weld is used in the strength function. In fact this is equivalent to overturning the throat section on one side of the seam.

In figure 4.1 the throat sections considered in the two methods are shown. The resistant cross section of a fillet weld is assumed to be the throat section, given by throat depth (a) times the effective length (ℓ).
The throat depth (a) is the smallest height of the triangle inscribed in the cross section of the weld as indicated in figure 4.2.
The effective length (ℓ) coincides with the overall length of the seam, provided that, obviously, faulty ends due to tailing off are eliminated.

More information on the methods can be found in [5, 6].



a b

Figure 4.1: Throat sections considered:

a) actual throat section used in method 1, stress component method.

b) overturned throat section used in method 2, mean stress method.

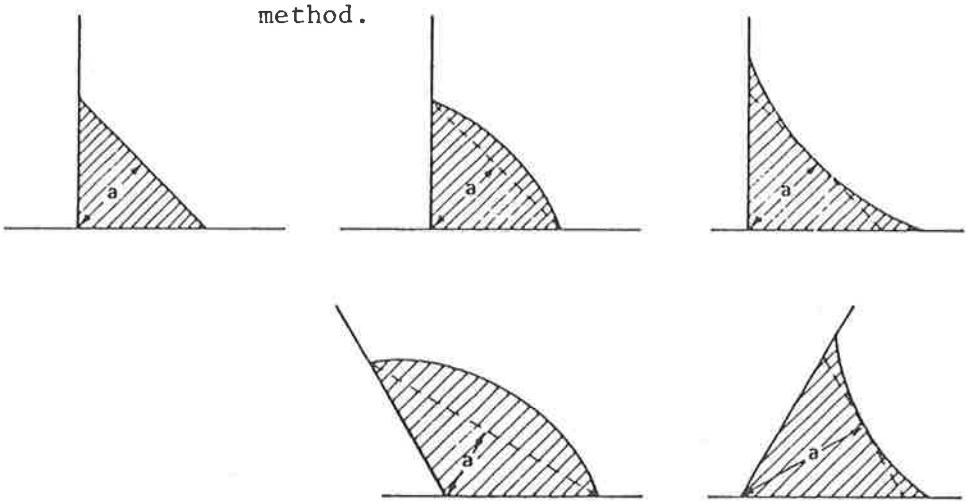


Figure 4.2: Throat depth a.

5. APPLICATION OF THE PROCEDURE TO THE FAILURE MECHANISM FOR WELDED CONNECTIONS

In this chapter some more background information will be provided on the failure mechanism and the strength functions. It will be shown how the original strength functions of EC 3 [1] have to be changed on the basis of the statistical evaluation of test results.

5.1 Method 1: stress component method

As mentioned in chapter 4, the actual throat section is assumed to be the resistant section. In a fillet weld the actual stress distribution in the plane of the cross section of the weld is complicated. The stress state changes from one point to another and considerable stress peaks are present (figure 5.1). However, stresses in fillet welds are usually considered

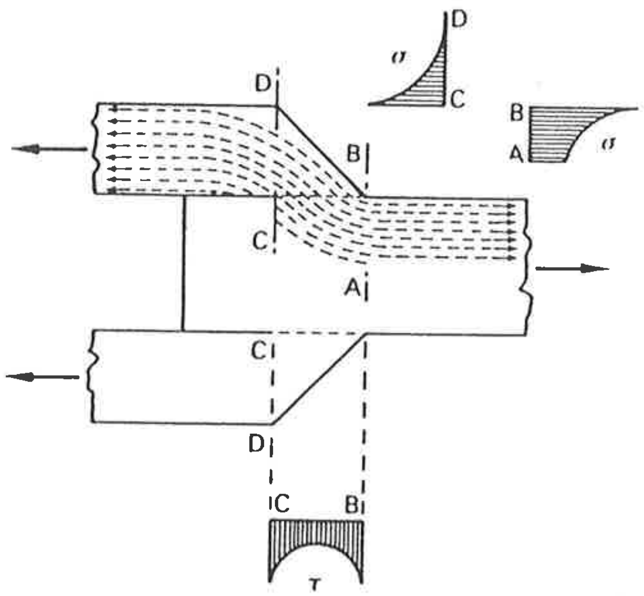


Figure 5.1: Actual stress distribution in a fillet welded joint (qualitatively).

uniformly distributed in the throat section. Substantially, this assumption is based on satisfactory ductility and toughness of material, which are checked by means of appropriately related control of welding material and qualification tests of the welding process. The following stress components are considered (figure 5.2):

- $\sigma_\perp$, the tensile or compressive stress acting perpendicularly to the actual throat section;
- $\tau_\perp$, the shear stress acting perpendicularly to the weld axis, lying in the actual throat section;
- $\tau_{//}$, the shear stress acting parallel to the weld axis, lying in the actual throat section;
- $\sigma_{//}$, the tensile or compressive stress acting parallel to the weld axis on its cross section.

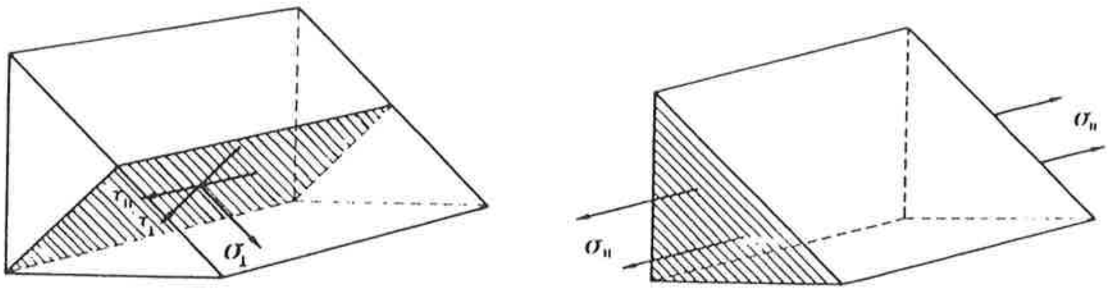


Figure 5.2: Stress components considered.

The latter stress component $\sigma_{//}$ has no significant influence on the weld strength. There has been a lively discussion on this subject. A summary of this discussion is given in [5]. In many codes, the stress component $\sigma_{//}$ is not in the strength functions for fillet welds. This holds for the strength functions presented below also. In fact, only the stress components $\sigma_\perp$, $\tau_\perp$ and $\tau_{//}$ are included.

Many tests were carried out to analyse fillet weld strength, in order to trace their ultimate surface in the space of co-ordinates $\sigma_\perp$, $\tau_\perp$, $\tau_{//}$. An important series of tests is the so-called "international test series" of 1968 [7], which was prompted by IIW. A study of the corresponding results influenced the choice of the various calculation methods.

The method proposed by ISO was based upon a description of the ultimate surface in the form of an ellipsoid of revolution determined by:

$$\frac{\sigma_{\perp}^2}{f_{u,w}^2} + \frac{\tau_{\perp}^2}{(0.75\ f_{u,w})^2} + \frac{\tau_{/\!/}^2}{(0.75\ f_{u,w})^2} = 1 \qquad \text{..... (5.1)}$$

This equation enables one to determine whether a plury-axial stress state characterized by $\sigma_{\perp}$, $\tau_{\perp}$ and $\tau_{/\!/}$ is acceptable or not. Now $1/0.75^2 \approx 1.8$ and if this is adopted, the equation (5.1) gives the verification condition:

$$\sqrt{\sigma_{\perp}^2 + 1.8\ (\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq f_{u,w} \qquad \text{..... (5.2)}$$

This formula was originally proposed by IIW and adopted by ISO. On the basis of the "international test series" [7] and discussions within IIW the formula was modified. The ultimate tensile strength of the fillet weld depends on electrode quality, which must be chosen in relation to the type of steel of which the elements to be welded are made. In general, therefore, the ultimate tensile strength of the weld $f_{u,w}$ can be expressed as a function of the strength f_u of the parent metal:

$$f_{u,w} = \beta_w\ f_u \qquad \text{..... (5.3)}$$

wherein β_w is the efficiency coefficient of the fillet weld. The general verification, therefore, becomes:

$$\sqrt{\sigma_{\perp}^2 + 1.8\ (\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq \beta_w\ f_u \qquad \text{..... (5.4)}$$

ISO has recommended this equation in the more general form:

$$\sqrt{\sigma_{\perp}^2 + k\ (\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq \beta_w\ f_u \qquad \text{..... (5.5)}$$

where the parameter k has not been fixed, so that the codes of the various countries are free to adopt different values of k, according to the chosen safety factor in shear. Some codes (and IIW also) adopt k = 3, in order to maintain, also for fillet welds, a combined stress formula similar to that of the Huber-Henky-Von Mises criterion. In this case, the equation becomes:

$$\sqrt{\sigma_{\perp}^2 + 3\,(\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq \beta_w\, f_u \qquad \text{..... (5.6)}$$

representing an ellipsoid having semi-axis $\tau_{\perp} = \tau_{/\!/} = 0.58\ \sigma$. Further tests have shown that the ellipsoid of ultimate strength cannot be considered as a solid of revolution, semi-axis $\tau_{/\!/}$ being longer than $\tau_{\perp}$. A generalization of the ISO equation (5.5) was therefore proposed as:

$$\sqrt{\sigma_{\perp}^2 + k_1\,\tau_{\perp}^2 + k_2\,\tau_{/\!/}^2} \leq \beta_w\, f_u \qquad \text{..... (5.7)}$$

where k_1/k_2 is about 3/2. Equation (5.6) therefore becomes:

$$\sqrt{\sigma_{\perp}^2 + 3\,\tau_{\perp}^2 + 2\,\tau_{/\!/}^2} \leq \beta_w\, f_u \qquad \text{..... (5.8)}$$

representing an ellipsoid having semi-axis $\tau_{/\!/} = 0.76\ \sigma_{\perp}$ and $\tau_{\perp} = 0.58\ \sigma_{\perp}$. This equation is closer than the ISO one to experimental results.

The ECCS Recommendations suggest the adoption of the β_w-values given in table 5.1 as a function of yield stress f_y of the material of which the welded elements are made. They allow the strength function of eqn. (5.6) to be adopted.

Table 5.1: β_w-values according to ECCS [4] and β-values according to ECCS [4] and EC 3 [1].

f_y (N/mm^2)	β_w	$\beta = 1/\beta_w$
≤ 240	1.43	0.7
> 240 ≤ 280	1.25	0.8
> 280 ≤ 340	1.18	0.85
> 340 ≤ 400	1.00	1.00

In EC 3 [1] the strength function of eqn. (5.6) was infact adopted also. It was however, modified using $\beta = 1/\beta_w$ and $f_u = 1.5\ f_y$ which is a good approximation for the steel grades considered. The strength function used in EC 3 [1] became:

$$\beta \sqrt{\sigma_\perp^2 + 3\ (\tau_\perp^2 + \tau_{/\!/}^2)} \leq 1.5\ f_y \qquad \text{..... (5.9)}$$

Adopting $\gamma_M = 1.5$ the design function used in EC 3 [1] became:

$$\beta \sqrt{\sigma_\perp^2 + 3\ (\tau_\perp^2 + \tau_{/\!/}^2)} \leq f_y \qquad \text{.... (5.10a)}$$

The following equation has been added:

$$\sigma_\perp \leq f_y \qquad \text{.... (5.10b)}$$

The β-value is given in table 5.1.

However, a format with γ_M expressed explicitly was preferred resulting in the following design function:

$$\sqrt{\sigma_\perp^2 + 3\ (\tau_\perp^2 + \tau_{/\!/}^2)} \leq \frac{f_u}{\beta\ \gamma_M} \quad ; \quad \gamma_M = 1.5 \qquad \text{.... (5.11a)}$$

$$\sigma_\perp \leq \frac{f_u}{\gamma_M} \qquad \text{.... (5.11b)}$$

A strength function based upon eqn. (5.11) has been used in the statistical evaluation procedure which is extensively reported in appendix I.1.

It turned out that only for FeE235 and FeE355 test results were available in large amounts. Furthermore large amounts of test results were available only for the weld configurations shown in figure 5.3. The statistical evaluation procedure revealed (see also [6, 7]) that the weld configuration having only

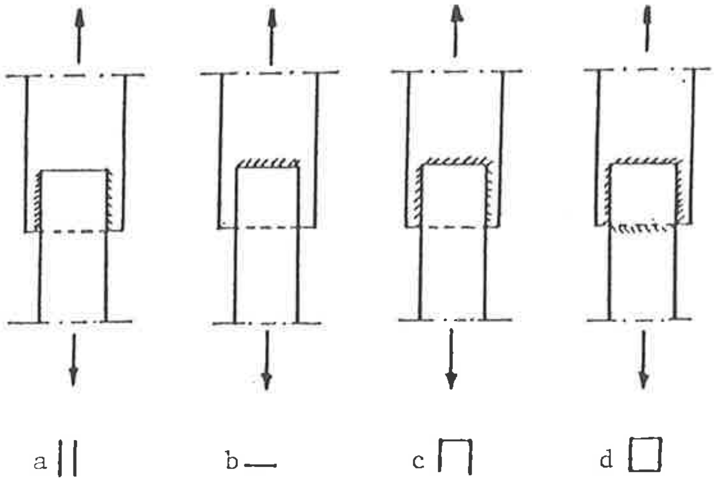


Figure 5.3: Weld configurations considered.

welds parallel to the load direction (figure 5.3a) is the most severe configuration. It was decided to optimize the strength function for this weld configuration, accepting some conservatism for the other weld configurations, since it does not seem practical to have different strength functions per weld configuration. Finally, the following design function can be achieved:

$$\sqrt{\sigma_{\perp}^2 + 3\ (\tau_{\perp}^2 + \tau_{/\!/}^2)} \leq \frac{f_u}{\beta\ \gamma_M} \quad ; \quad \gamma_M = 1.25 \qquad \text{.... (5.12a)}$$

$$\sigma_{\perp} \leq \frac{f_u}{\gamma_M} \qquad \text{.... (5.12b)}$$

with β-values according to table 5.2.

Table 5.2: β-values according to statistical evaluations of appendix I.

steel grade	β	f_u (N/mm^2)
FeE235	0.74	360
FeE355	0.77	510

In figure 5.4 the results of the statistical analysis for the strength function using table 5.1 (1984 Draft) are compared with those for the strength function using table 5.2 (1988 Revision). The outcome of the statistical evaluation is represented by values for γ_M, ΔK and γ_M^* [3]. First of all the results obtained, using the strength function of the 1984 Draft, are considered. For all weld configurations treated together and for weld configuration ||, both made of FeE235, γ_M^*-values are greater than 1.25. These values are lower than 1.25 in all other cases. For FeE355 very conservative results are obtained with $\gamma_M^* < 1.00$. Considering the results obtained, using the strength function of the 1988 Revision, it can be concluded that γ_M^*-values just a bit lower than 1.25 are obtained for the weld configurations || of both materials. For all other weld configurations lower values for γ_M^* are obtained. Therefore a harmonised value $\gamma_M = 1.25$ can be used in eqn. (5.12) with β-values according to table 5.2.

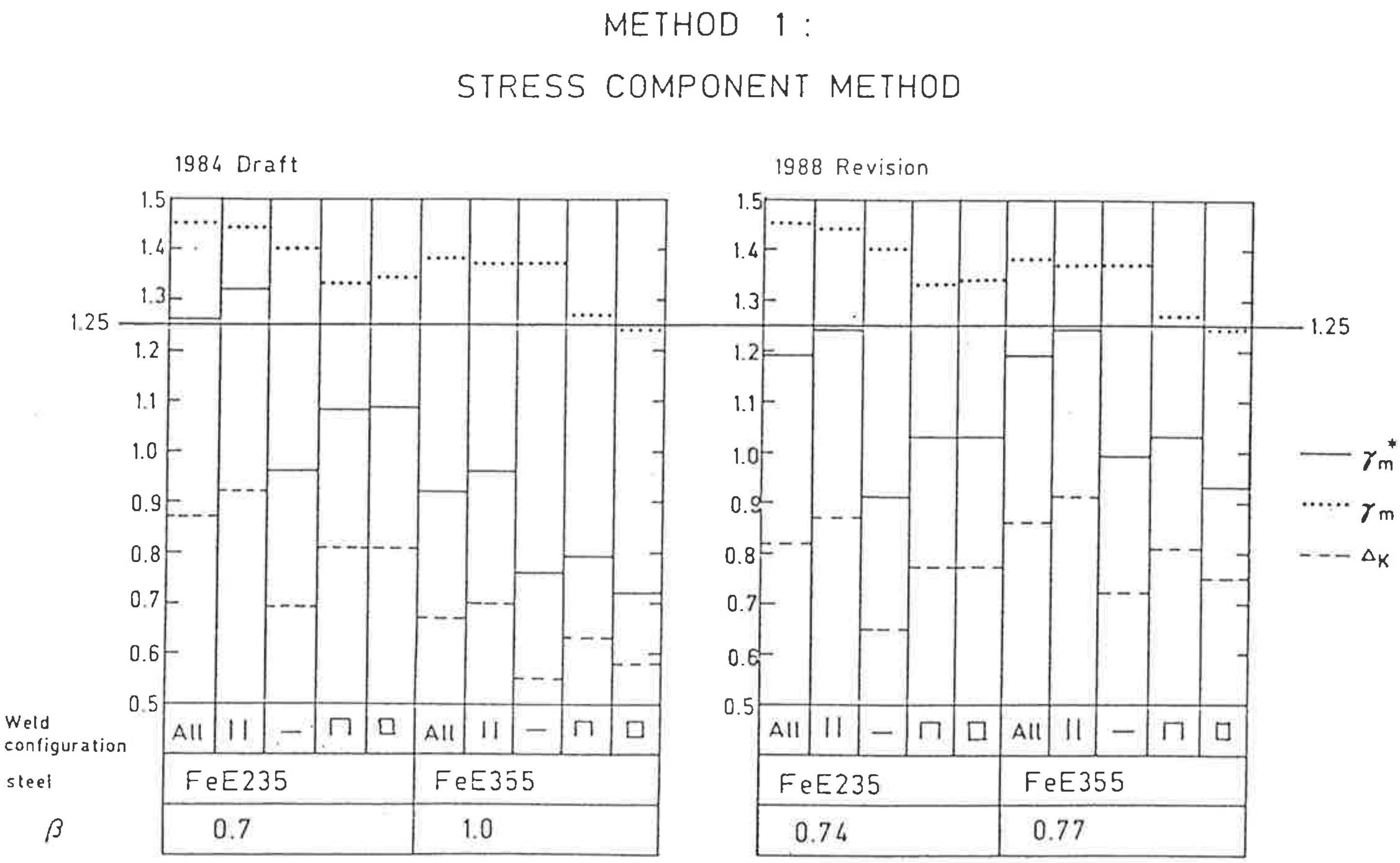


Figure 5.4: Comparison of statistical analyses for method 1: stress component method.

In the figures 5.5 and 5.6 the test results r_{ei} have been plotted versus the theoretical resistances r_{ti} based upon the strength function using table 5.2 for the materials FeE235 and FeE355 respectively. The corresponding sensitivity diagrams for weld configuration are given in the figures 5.7 and 5.8.

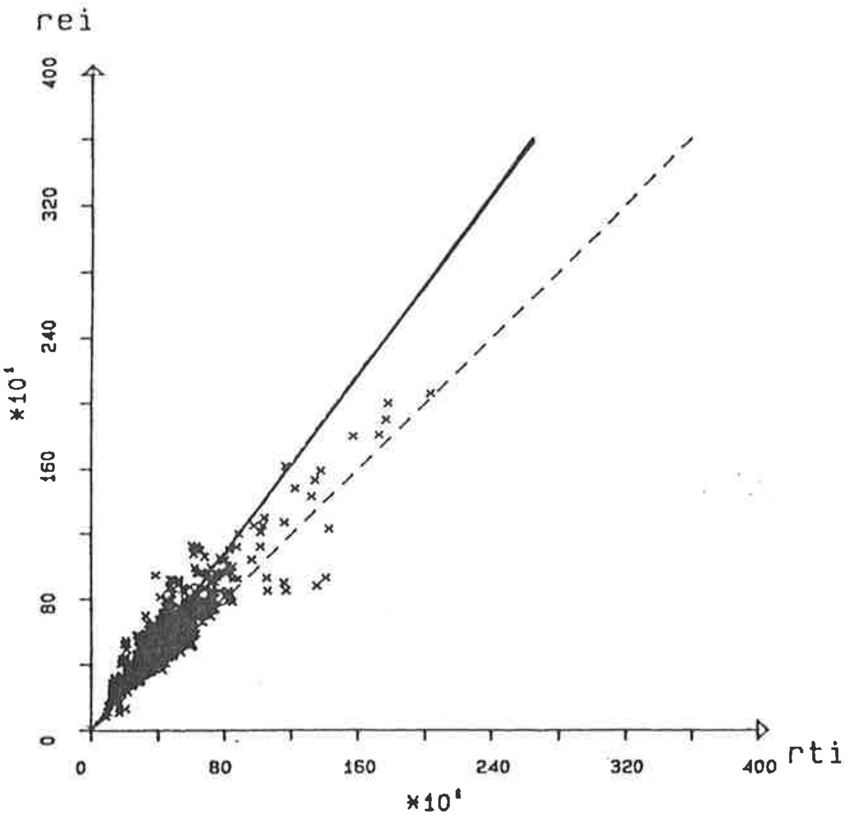


Figure 5.5: Test results r_{ei} versus theoretical resistances r_{ti} based upon the strength function using table 5.2 for method 1: stress component method; FeE235, $\bar{b}$ = 1.362.

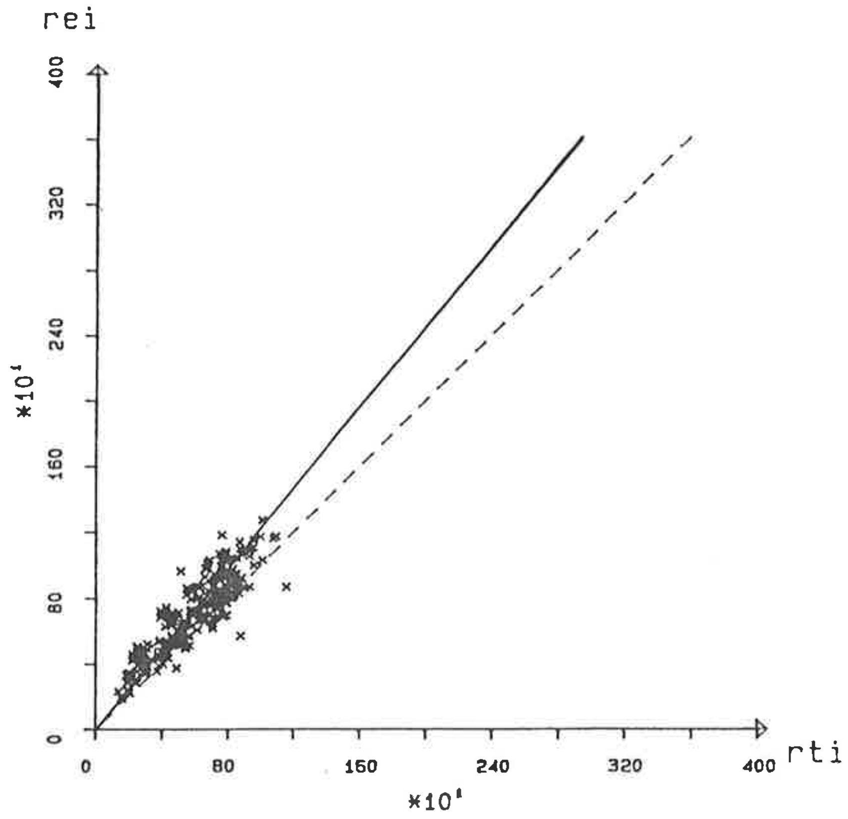


Figure 5.6: Test results r_{ei} versus theoretical resistances r_{ti} based upon the strength function using table 5.2 for method 1: stress component method; FeE355, $\bar{b}$ = 1.224.

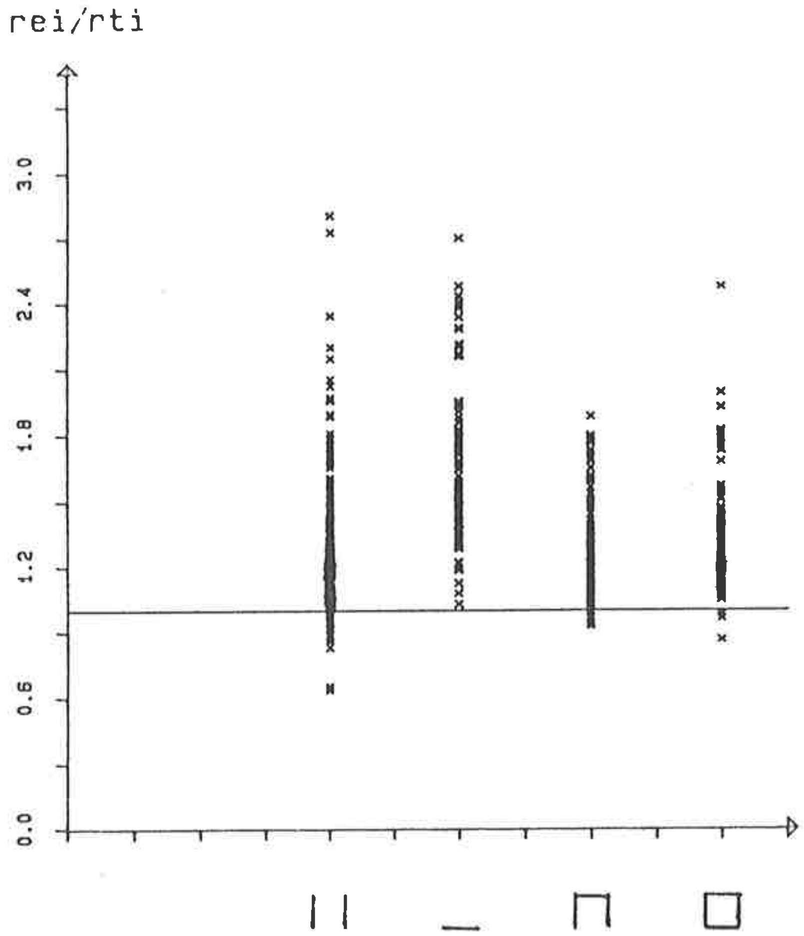


Figure 5.7: Sensitivity diagram for weld configuration, FeE235, method 1: stress component method.

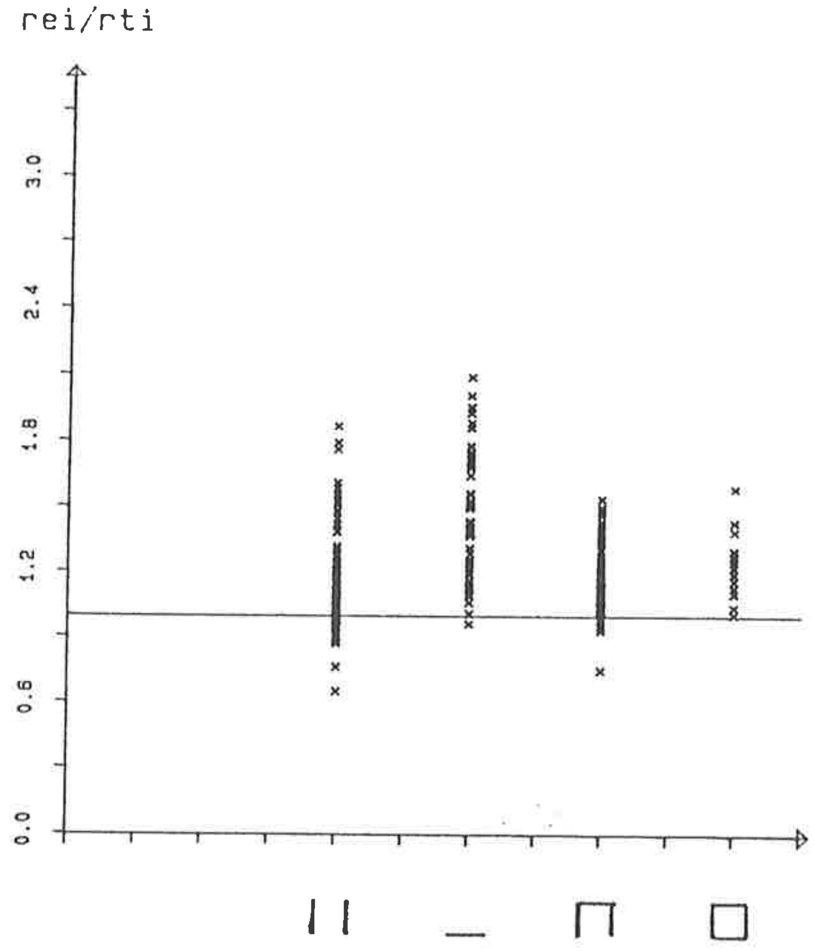


Figure 5.8: Sensitivity diagram for weld configuration, FeE355, method 1: stress component method.

5.2 Method 2: mean stress method

As mentioned in chapter 4, the overturned throat section can be regarded to be the resistant section. The mean stress σ_w on the throat section is the stress parameter to be considered (figure 5.9).

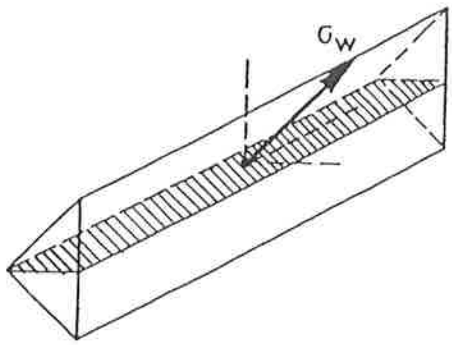


Figure 5.9: Mean stress σ_w.

This mean stress is obtained by dividing the force F on the weld by the throat area $A = a\ell$:

$$\sigma_w = \frac{F}{A} = \frac{F}{a\ell} \qquad \ldots\ldots (5.13)$$

In [7], on the basis of a statistical evaluation of the international test series, the following design function is proposed:

$$F \leq F_i = 0.8\ (A_1 + A_2)\ f_{u,w} \qquad \ldots\ldots (5.14)$$

This formula is derived for the weld configurations of figure 5.3. The throat area A_1 refers to welds perpendicular to the loading direction; A_2 refers to welds parallel to the loading direction. For one weld, eqn. (5.14) can be rewritten as follows:

$$\sigma_w = \frac{F}{a\ell} \leq 0.8\ f_{u,w} \qquad \ldots\ldots (5.15)$$

For $f_{u,w}$ the following equation may be used:

$$f_{u,w} = \frac{f_u + f_{u,wm}}{2} \qquad \text{..... (5.16)}$$

For practical reasons $f_{u,w} = 450$ N/mm^2 for FeE235 and $f_{u,w} = 550$ N/mm^2 for FeE355 may be used.

Others, e.g. [6], use the ultimate shear strength of the weld as value not to be exceeded in stead of 0.8 $f_{u,w}$:

$$\sigma_w = \frac{F}{a\ell} \leq \tau_{u,w} \qquad \text{..... (5.17)}$$

Now, it is assumed that the ultimate shear strength of the weld $\tau_{u,w}$ can be expressed as a function of the shear strength τ_u of the parent metal:

$$\tau_{u,w} = \beta_w \tau_u \qquad \text{..... (5.18)}$$

Eqn. (5.17) can be written as:

$$\sigma_w \leq \beta_w \tau_u \qquad \text{..... (5.19)}$$

With $\tau_u = f_u/\sqrt{3}$, $\beta = 1/\beta_w$ and $f_u = 1.5\ f_y$ eqn. (5.19) can be rewritten as:

$$\sigma_w \leq \frac{1.5\ f_y}{\beta\ \sqrt{3}} \qquad \text{..... (5.20)}$$

which is the strength function of EC 3 [1]. The corresponding design function (with $\gamma_M = 1.5$) is:

$$\sigma_w \leq \frac{f_y}{\beta\ \sqrt{3}} \qquad \text{..... (5.21)}$$

The β-value is given in table 5.1.
However, a format with γ_M expressed explicitly was preferred resulting in the following design function:

$$\sigma_w \leq \frac{f_u}{\beta\ \gamma_M\ \sqrt{3}} \quad ; \quad \gamma_M = 1.5 \qquad \text{..... (5.22)}$$

A strength function based on eqn. (5.22) has been used in the statistical evaluation procedure which is extensively reported in appendix I.2.

For the test results available and the outcome of the statistical evaluation the same as stated in section 5.1 holds, resulting in the following design function:

$$\sigma_w \leq \frac{f_u}{\beta \ \gamma_M \sqrt{3}} \quad ; \quad \gamma_M = 1.25 \qquad \text{..... (5.23)}$$

where:

$$\sigma_w = \frac{F}{\Sigma \ a\ell}$$

and β-values are according to table 5.2.

Note that for the determining weld configuration, being the one having welds parallel to the load direction only (figure 5.3a), method 1 and method 2 result in the same ultimate strength as can be seen in figure 5.10.

Method 1:

$$\sigma_{\perp} = 0$$

$$\tau_{\perp} = 0$$

$$\tau_{/\!/} = \frac{F_i}{a\ell}$$

$$\sqrt{\sigma_{\perp}^2 + 3\,(\tau_{\perp}^2 + \tau_{/\!/}^2)} =$$

$$\sqrt{3\,\left(\frac{F_i}{a\ell}\right)^2} =$$

$$\frac{F_i\,\sqrt{3}}{a\ell} = \frac{f_u}{\beta\,\gamma_M}$$

$$F_i = \frac{f_u\,a\ell}{\beta\,\gamma_M\,\sqrt{3}}$$

Method 2:

$$\sigma_w = \frac{F}{\Sigma\, a\ell} = \frac{F_i}{a\ell}$$

$$\sigma_w =$$

$$\frac{F_i}{a\ell} = \frac{f_u}{\beta\,\gamma_M\,\sqrt{3}}$$

$$F_i = \frac{f_u\,a\ell}{\beta\,\gamma_M\,\sqrt{3}}$$

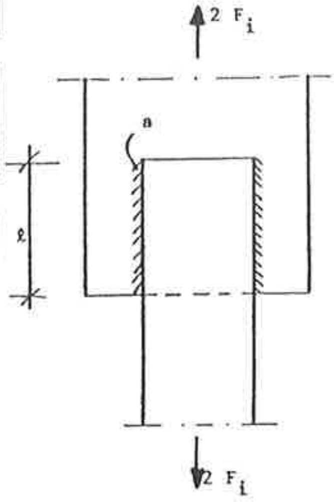


Figure 5.10: Comparison of the methods 1 and 2 for determining weld configuration.

In figure 5.11 the results of the statistical analysis for the strength function using table 5.1 (1984 Draft) are compared with those for the strength function using table 5.2 (1988 Revision). The outcome of the statistical evaluation is represented by values for γ_M, ΔK and γ_M^* [3]. First of all the results obtained, using the strength function of the 1984 Draft, are considered. For all weld configurations treated together and for weld configuration ||, both made of FeE235, γ_M^*-values are greater than 1.25. These values are lower than 1.25 in all other cases. For FeE355 very conservative results are obtained with $\gamma_M^* < 1.00$. Considering the results obtained, using the strength function of the 1988 Revision, it can be concluded that γ_M^*-values just a bit lower than 1.25 are obtained for the weld configurations || of both materials. For all other weld configurations lower values for γ_M^* are obtained except for all weld configurations treated together. Therefore a harmonised value $\gamma_M = 1.25$ can be used in eqn. (5.23) with β-values according to table 5.2.

METHOD 2 :

MEAN STRESS METHOD

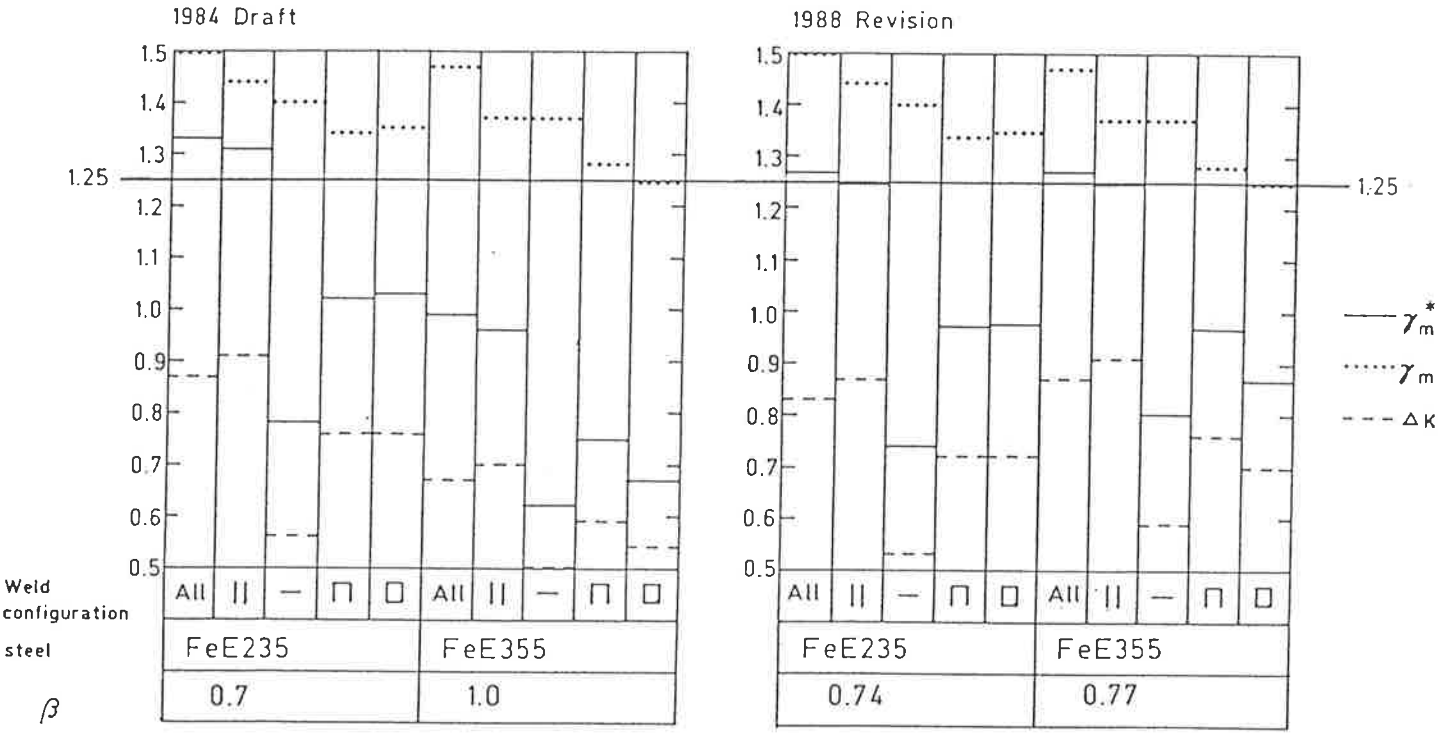


Figure 5.11: Comparison of statistical analyses for method 2: mean stress method.

In the figure 5.12 and 5.13 the test results r_{ei} have been plotted versus the theoretical resistances r_{ti} based upon the strength function using table 5.2 for the materials FeE235 and FeE355 respectievely. The corresponding sensitivity diagrams for weld configuration are given in the figures 5.14 and 5.15.

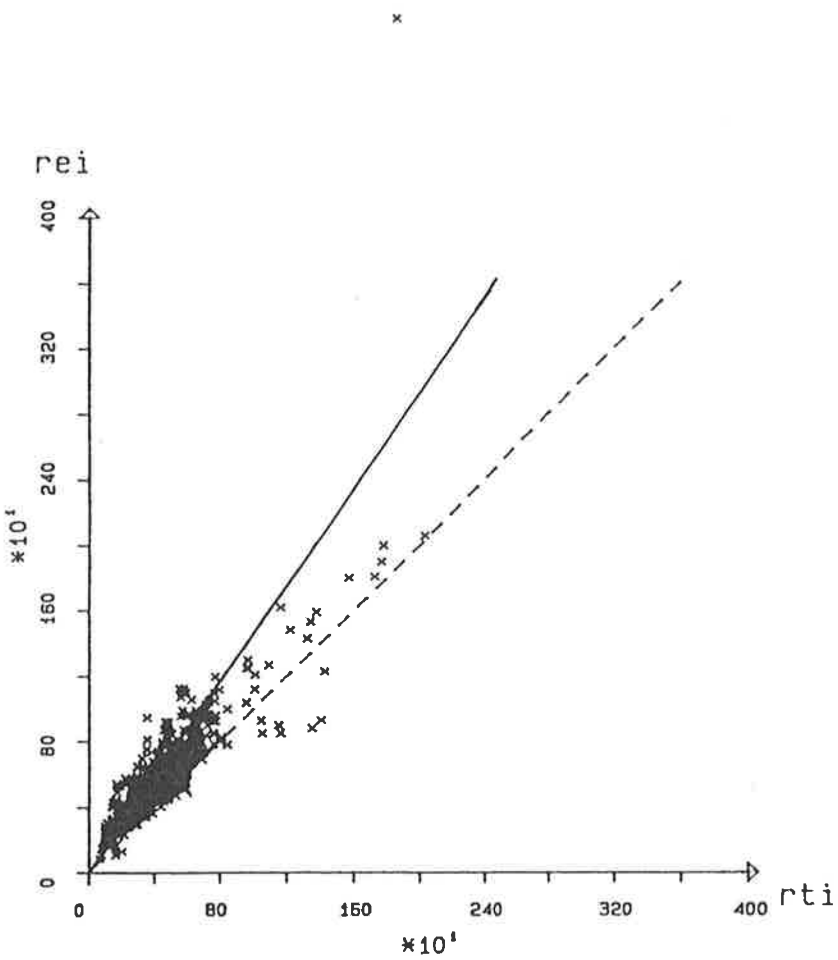


Figure 5.12: Test results r_{ei} versus theoretical resistances r_{ti} based upon the strength function using table 5.2 for method 2: mean stress method, FeE235, $\bar{b}$ = 1.472.

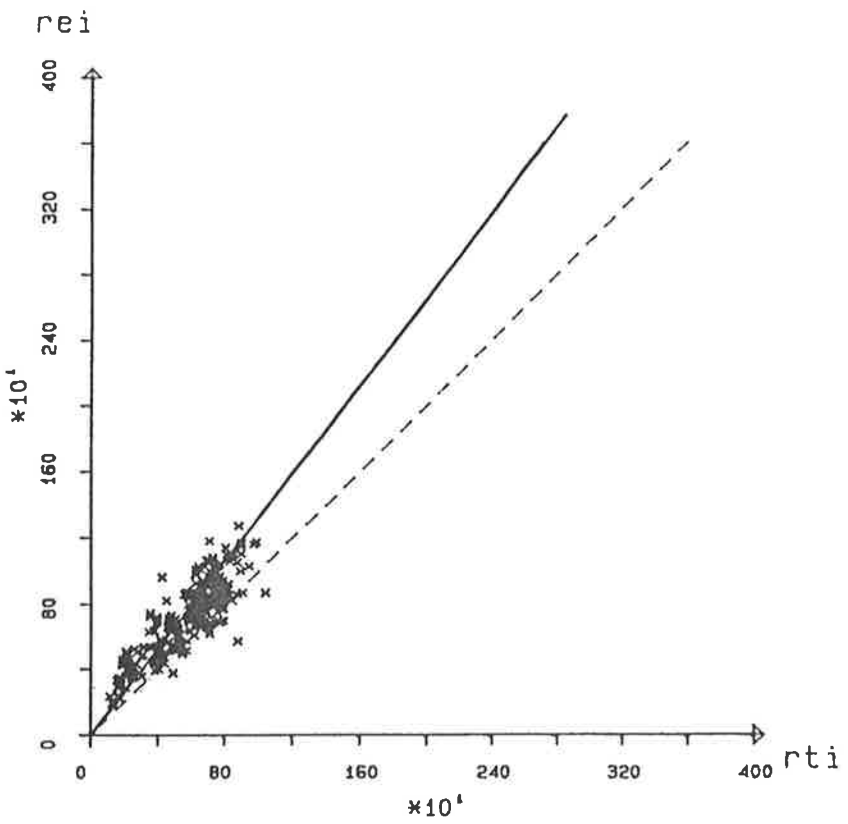


Figure 5.13: Test results r_{ei} versus theoretical resistances r_{ti} based upon the strength function using table 5.2 for method 2: mean stress method; FeE355, $\bar{b}$ = 1.327.

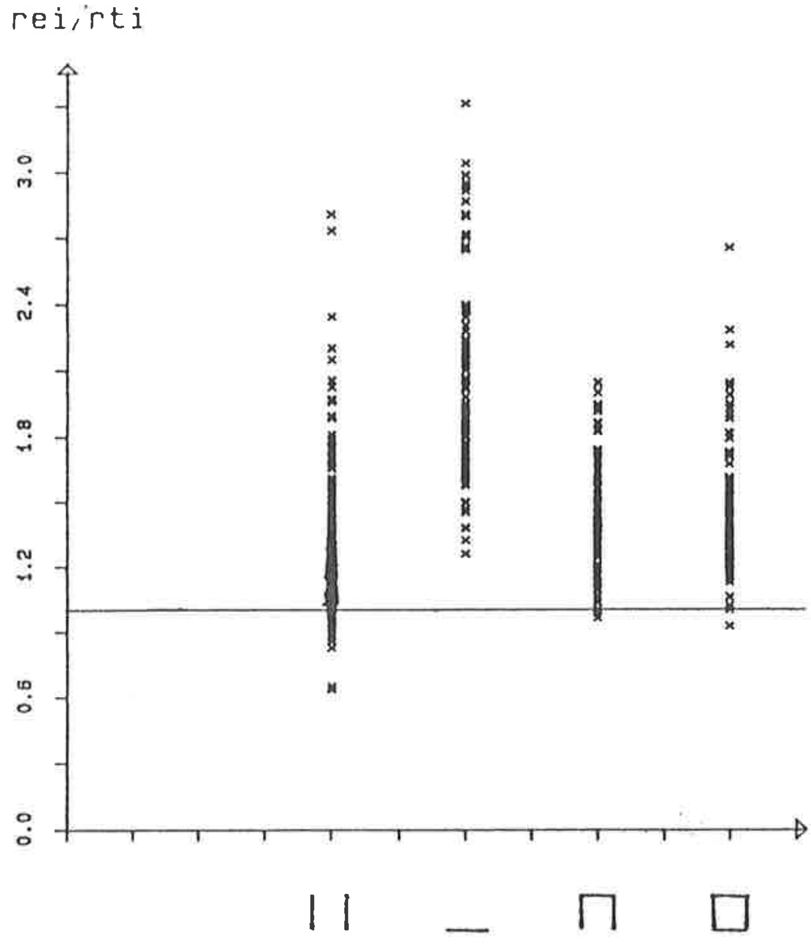


Figure 5.14: Sensitivity diagram for weld configuration, FeE235, method 2: mean stress method.

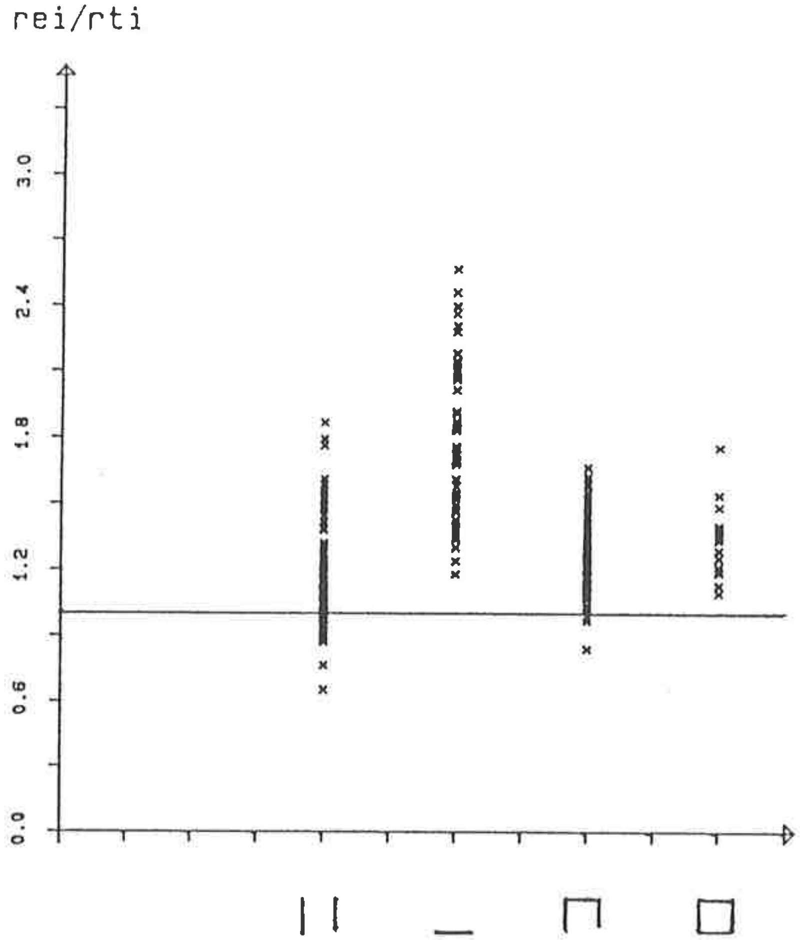


Figure 5.15: Sensitivity diagram for weld configuration, FeE355, method 2: mean stress method.

6. DISCUSSION AND CONCLUSIONS

On the basis of the statistical evaluation of available test results, the following design functions for fillet welds have been derived:

$$\text{method 1:} \quad \sqrt{\sigma^2 + 3\,(\tau^2 + \tau^2)} \leq \frac{f_u}{\beta\ \gamma} \qquad \text{..... (6.1a)}$$

$$\sigma \leq \frac{f_u}{\gamma_M} \qquad \text{..... (6.1b)}$$

$$\text{method 2:} \quad \frac{F}{\Sigma\ a\ell} \leq \frac{f_u}{\beta\ \gamma_M\ \sqrt{3}} \qquad \text{..... (6.2)}$$

where $\gamma_M = 1.25$ and $\beta = 0.74$ for FeE235
$\beta = 0.77$ for FeE355

Only a minor difference in β-value is obtained for FeE235 and FeE355. This can be explained as follows. The static strength of the finished weld is influenced by the strength of weld and parent material. By making a statistical analysis of the relation between weld and parent material, a mean value and standard deviation can be obtained for the ratio $f_{u,wm}/f_u$. For steel grade FeE235 the mean value is greater than for steel grade FeE355. This is due to the fact that the same electrodes are used for these steel grades. The standard deviation for FeE235 is greater than the one for FeE355. Using $\beta = 0.74$ for FeE235 and the outcome of the statistical analysis mentioned above, a β-value for FeE355 can be derived which is between $\beta = 0.77$ and $\beta = 0.88$ depending on the assumption for the relation between $f_{u,w}$ and $f_{u,wm}$ and f_u:

- for $f_{u,w} = (f_{u,wm} + f_u)/2$ the β-value is $\beta = 0.77$;
- for $f_{u,w} = f_{u,wm}$ the β-value is $\beta = 0.88$.

This derivation has been carried out with 5% fractiles of the ratio $f_{u,wm}/f_u$. It can be concluded that the value $\beta = 0.77$ for FeE355 as obtained in the statistical evaluation corresponds to the value $\beta = 0.74$ for FeE235.

It should be mentioned that a design function which includes both f_u and $f_{u,wm}$ may be an alternative for future investigations, especially in relation to high strength steel.

The design functions (6.1) and (6.2) allow fillet welds to carry more load than design functions proposed by the IIW. There are reasons why the design functions above, as derived by statistical evaluation, should be modified into more conservative ones. Some of these reasons are given below:

- The design functions were derived for FeE235 and FeE355 only while they will be applied for other steel grades as well.
- The design functions were derived for a limited amount of weld configurations. For example, formally, the T-joint is not covered while the design functions will be used for this case as well.
- Design functions should be such that they allow for certain weld discontinuities to be present. No information is available on weld discontinuities in the available tests. If there were no weld discontinuities in the tests then these tests may be too optimistic.
- Weld strength depends on the quality of the fabrication process also. A designer does not always have appropriate influence on fabrication.

For these reasons, the β-values are increased to $\beta = 0.8$ for FeE235 and $\beta = 0.9$ for FeE355.

In table 6.1 the strength parameters $f_u/(\beta\ \gamma_M)$ of method 1 are compared. The new β-values result in a decrease in $f_u/(\beta\ \gamma_M)$ of 7.5 and 15% for FeE235 and FeE355 respectively when compared to the β-values according to the statistical evaluation. The IIW design function is still more conservative than the design function with the new β-values.

Table 6.1: Comparison of strength parameter $\dfrac{f_u}{\beta\ \gamma_M}$ of method 1.

Steel grade	f_u	Statistical evaluation				IIW				EC 3 Rev.			
	N/mm^2	β	γ_M	$\beta\ \gamma_M$	$\frac{f_u}{\beta\ \gamma_M}$ N/mm^2	β	γ_M	$\beta\ \gamma_M$	$\frac{f_u}{\beta\ \gamma_M}$ N/mm^2	β	γ_M	$\beta\ \gamma_M$	$\frac{f_u}{\beta\ \gamma_M}$ N/mm^2
FeE235	360	0.74	1.25	0.93	389	0.7 (0.84)	1.5 (1.25)	1.05	343	0.8	1.25	1.00	360
FeE355	510	0.77	1.25	0.96	530	0.85 (1.02)	1.5 (1.25)	1.28	400	0.9	1.25	1.13	453

In this report strength functions and suitable model factors for welded connections have been determined, using the statistical procedure of [3] to derive the strength functions from the available test data of [2].

In table 6.2 the strength functions are summarized. In the first column of table 6.2 the methods used are mentioned. In the second column the strength functions are given as presented in the 1984 draft Eurocode No.3 [1]. These strength functions have been reformatted to, among others, write the model factors explicitly: the third column of table 6.2. In the last column, the strength functions as proposed for the 1988 revision of Eurocode No. 3 are given. These strength functions are based upon the statistical evaluation of test results and upon the considerations mentioned above.

Table 6.2: Summary of design functions for welded connections.

method	EC No. 3 draft 1984 [1]	EC No. 3 draft 1984 [1] reformatted	EC No. 3 revision 1988
1: stress component method	$\beta \sqrt{\sigma_\perp^2+3(\tau_\perp^2+\tau_{/\!/}^2)} \leq f_y$ and $\sigma_\perp \leq f_y$ where: $\beta = 0.7$ if $f_y \leq 240$ N/mm^2 $\beta = 1.0$ if $f_y \geq 340$ N/mm^2	$\sqrt{\sigma_\perp^2+3(\tau_\perp^2+\tau_{/\!/}^2)} \leq \frac{f_u}{\beta\,\gamma_M}$ and $\sigma_\perp \leq \frac{f_u}{\gamma_M}$ where: $\beta = 0.7$ if $f_y \leq 240$ N/mm^2 $\beta = 1.0$ if $f_y \geq 340$ N/mm^2 ($\gamma_M = 1.5$; $f_u = 1.5\ f_y$)	$\sqrt{\sigma_\perp^2+3(\tau_\perp^2+\tau_{/\!/}^2)} \leq \frac{f_u}{\beta\,\gamma_M}$ and $\sigma_\perp \leq \frac{f_u}{\gamma_M}$ where: $\beta = 0.8$ if $f_u = 360$ N/mm^2 $\beta = 0.9$ if $f_u = 510$ N/mm^2 ($\gamma_M = 1.25$)
2: mean stress method	$\sigma_w \leq \frac{f_y}{\beta\,\sqrt{3}}$ where: $\sigma_w = \frac{F}{\Sigma\ a\ell}$ $\beta = 0.7$ if $f_y \leq 240$ N/mm^2 $\beta = 1.0$ if $f_y \geq 340$ N/mm^2	$\sigma_w \leq \frac{f_u}{\beta\,\gamma_M\,\sqrt{3}}$ where: $\sigma_w = \frac{F}{\Sigma\ a\ell}$ $\beta = 0.7$ if $f_y \leq 240$ N/mm^2 $\beta = 1.0$ if $f_y \geq 340$ N/mm^2 ($\gamma_M = 1.5$; $f_u = 1.5\ f_y$)	$\sigma_w \leq \frac{f_u}{\beta\,\gamma_M\,\sqrt{3}}$ where: $\sigma_w = \frac{F}{\Sigma\ a\ell}$ $\beta = 0.8$ if $f_u = 360$ N/mm^2 $\beta = 0.9$ if $f_u = 510$ N/mm^2 ($\gamma_M = 1.25$)

- β-values relevant for FeE235 and FeE355 have been given only. β-values for other steel grades for the 1988 revision of EC 3 can be obtained by linear interpolation and extrapolation. This results in approximately: $\beta = 0.85$ if $f_u = 430$ N/mm^2 and $\beta = 1.00$ if $f_u = 650$ N/mm^2.

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