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Calibration of probability of failure estimates made from probabilistic fracture mechanics analysis

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Calibration of probability of failure estimates made from probabilistic fracture mechanics analysis

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SUMMARY

Background

Fracture mechanics procedures given in BSI PD6493:1991 and the Draft BS 7910:1999 are based on the concept of the failure assessment diagrams (FAD's). However, validation studies have shown that assessment points falling outside these diagrams do not necessarily represent failure confirming the presence of some modelling uncertainty in the FAD's.

Objectives

The present work is aimed at using the results of validation studies to estimate the uncertainty in the Level 2 FAD. Statistical analyses of the validation data is conducted to derive the modelling uncertainty which is then applied in example calculations to explore the effect on failure probability estimates.

Conclusions

- The margin of safety and hence the modelling uncertainty varies around the failure assessment diagram (FAD) with the highest margin in the elastic region and the minimum around the knee (i.e. elastic-plastic) region. However, the data is characterised by a large amount of scatter.

- The Weibull and loge-normal distributions were found to fit the modelling uncertainty (M_u) well, when described in terms of the difference in radial distances from the assessment point and failure line to the FAD origin.

- Including the modelling uncertainty in the probabilistic fracture mechanics calculation in general reduced the failure probability (P_f) estimate slightly; typically this was less than by one order of magnitude. For the elastic region, where the highest margins were observed, P_f was reduced by about one order of magnitude.

- From the reduction observed in failure probability estimates, it may be stated the current PSF's in the Draft BS 7910 correspond to slightly lower target failure probabilities than the specified values.

- In general, the current Draft BSI 7910 partial safety factors (PSF's) are unlikely to be significantly changed by including modelling uncertainty in the probabilistic fracture mechanics calculations, but there may be merit in a re-analysis to derive new PSF's particularly for the lowest target failure probabilities (e.g. $7x10^{-5}$ and $1x10^{-5}$).

- The statistical distributions derived in this study may be included in probabilistic analyses provided that the limit state equation has been formulated in terms of differences in radial distance from the FAD origin.

1. INTRODUCTION

Fracture mechanics procedures given in BSI PD6493:1991[1] and the Draft BS 7910:1999[2] are based on the well known concept of the failure assessment diagram (FAD). It is also known from validation studies that assessment points falling outside these diagrams do not necessarily represent failure. Therefore, there is a modelling uncertainty associated with the FAD's.

The partial safety factors given in both PD6493:1991 and the Draft BS 7910:1999 were derived from probabilistic fracture mechanics analyses which did not make any allowance for modelling uncertainty in the relevant FADs. Thus any assessment falling outside the assessment line in the FAD is classed as failure. It is believed that more realistic estimates of failure probability and partial safety factors could be made if the modelling uncertainty in the FAD were included in the probabilistic analyses.

The present work is aimed at using the results of validation studies to estimate the uncertainty in the Level 2 FAD. Statistical analyses of the validation data is conducted to derive the modelling uncertainty which is then applied in example calculations to explore the effect on failure probability estimates.

2. WIDE PLATE AND STRUCTURAL TEST DATA

In 1995, Challenger et al[3] reported the results of an extensive validation study of the PD6493:1991 fracture assessment procedures. The study was based on data generated over the years at TWI and some other published data. It consisted mainly of wide plate test results covering several materials groups including pressure vessel and pipeline steels and aluminium alloys. The data also included some pressure vessel and pipe tests.

Most of the results presented by Challenger for validating the Level 2 procedures were utilised in the present work. The details of the tests such as the material type, specimen geometry, tensile properties and fracture toughness values, and the calculated K_r (or $\sqrt{\delta_r}$) and S_r were recorded on an EXCEL spreadsheet.

In most cases, the same test data was analysed in terms of both K and CTOD[3]. Two sets of analyses were therefore carried out in the present work in terms of both parameters. Challenger et al also analysed some test data using the PD6493:1991 Level 3 procedures based on R-Curve generated from small-scale specimens. These data have not been included in the present study.

3. UNCERTAINTY IN FAILURE ASSESSMENT DIAGRAM

3.1 GENERAL

The validation data available was filtered to obtain the most appropriate data set for the analyses. In a number of cases, the same test results were presented using different assumptions in the analysis. Such results were reviewed to decide on the appropriate set of results to include in this study. For example, there were results based on assuming yield magnitude residual stresses and others based on measured residual stresses. It was decided to include the results based on yield magnitude residual stresses in these cases as this represents the most common situation in fracture assessments. In other cases the results of wide plate tests were presented based on different assumptions regarding the fracture toughness. Again, the most appropriate results were selected for this study.

The data used in this study are shown along with the Level 2 FAD in Fig.1 and 2 in terms of K and CTOD respectively. There were 90 and 205 data points in terms of K and CTOD respectively. The analysis procedure adopted for the two data sets is exactly the same, however each set was examined in two different ways.

In order to quantify the modelling uncertainty in the FAD, a measure is required of the relationship between the assessment line and actual component failure point. Figure 3 illustrates the approaches adopted. For a failure point A, a measure of the uncertainty in prediction of the model could be obtained by comparing the radial distances R and r from the origin to the point and FAD respectively. In the classical 'safety factor' format, the ratio R/r could be used as the measure. An alternative measure of the uncertainty is also obtained from the difference R-r. The available data have been examined using both formats in the present work.

While Fig.3 illustrates the uncertainty measure with respect to one failure point, the procedure has to be applied to every data point available and the general trend identified.

3.2 VARIATION OF MODELLING UNCERTAINTY (M_U) WITH FAD REGIONS

An examination of the wide plate data (see Fig.1 and 2) shows the presence of a variation in behaviour with regions of the FAD. It can be clearly seen that the failure points are much closer to the FAD in the knee (elastic-plastic) region than in other regions. Also the data points appear to be less scattered in the knee region. It was therefore decided to examine the variation of M_u with the angle θ between the S_r-axis and a line from the origin to the assessment point (see Fig.3).

There were a total of 90 data points analysed using a K-based Level 2 procedure. The modelling uncertainty associated with these data points are presented in Fig.4 and 5 in terms of R-r (M_u) and R/r (M_u') respectively. For CTOD-based assessments, a total of 205 data points (including the 90 presented also in terms of K) were available. The modelling uncertainty based on these results are plotted in Fig.6 and 7 in terms of R-r and R/r respectively. A mean regression line is also shown in each of Fig.4-7.

From Fig.4-7, it can be seen that the general trend in the variation of the uncertainty (M_u) with angle θ is consistent regardless of the format (R-r or R/r) used. It is clear that both formulations are different implementations of the same quantity and may be treated as equivalent. The general trend that emerges is that on average the margin of safety on the FAD is minimum in the middle (elastic-plastic) region, slightly higher in the 'plastic collapse' region and maximum in the 'fracture' region. However, this overall trend is complicated by the varying degree of scatter in the different regions.

Comparing the uncertainty associated with the CTOD-based data and the K-based data (e.g., see Fig.4 and 6) shows a higher degree of scatter in the K-based results than the CTOD-based results, particularly in the middle region. This may simply be because there were more CTOD-based (205 points) data than the K-based data (90 points). However, statistical analysis was conducted on each set of data.

3.3 STATISTICAL ANALYSIS OF DATA

The ultimate objective of the analysis of the uncertainty data is to derive a statistical distribution that can be used in a probabilistic or reliability analysis. In this project, the reliability calculations were performed using the TWI FORM/MONTE software. The limit state function in this program is based on the difference in radial distance from the FAD origin to the assessment point (R) and that to the assessment line (r). Therefore the appropriate format for introducing the modelling uncertainty into FORM/MONTE would be the ‘R-r’ format. For this report therefore, statistical analysis has been conducted only on the data in the ‘R-r’ format for both K-based and CTOD-based results.

The data were divided into three equal regions (Fig.8) in order to explore the general trend discussed in the preceding section. A number of statistical distributions were fitted to the data falling in each region and also to all the data combined. Two of the data points for both the K and CTOD-based analyses fell inside the FAD thereby giving negative R-r values; so a constant value was added to all calculated R-r values prior to distribution fitting. This was necessary as the software packages used for the statistical analyses could only accept values greater than zero in fitting data to non-normal distributions. This modification of the data amounted to introducing a location parameter or a threshold value corresponding to the minimum data value. The minimum calculated R-r values were -0.059 and -0.115 for the K and CTOD-based data respectively; so location parameters were fixed at -0.06 and -0.12.

The statistical analyses were conducted using the MINITAB software package and the TWI program DISTFIT. Both programs use the Maximum likelihood method to estimate parameters assuming normal, $\log_e$-normal, exponential and Weibull distributions. DISTFIT gives the parameter estimates as well as the Kolmogorov-Smirnov statistic D* which is a measure of the maximum deviation of the assumed distribution from the data. The best fit is the distribution with the minimum value of D*. On the other hand, goodness of fit is judged graphically in MINITAB by examining the probability plots. The choice is generally based on how close the points fall to the straight line, particularly in the tail regions of the distribution.

For each analysis case, MINITAB was first used to obtain probability plots for all four distributions on a single page (e.g., see Fig 9). The likely best fits were identified in this way. Then parameter estimates and the corresponding D* values were obtained from DISTFIT (e.g., see Table 1). In practically all cases, the parameter estimates were the same from both programs, and in general, the D* values confirmed the visual judgements made from the probability plots. In effect, both MINITAB and DISTFIT indicated the same best fit distributions in all the cases analysed.

A summary of the results of the statistical analyses is given in Table 2 and 3 for the K-based and CTOD-based data. This agrees with the general trend observed in Fig.4-7 earlier with a minimum mean (R-r) value in the elastic plastic region, a slightly higher value in the plastic collapse region and the highest value in the ‘fracture’ dominated region. The order of the standard deviation values is similar to that of the mean values. It is noted that these standard deviations represent high degree of scatter on the mean values.

4. USE OF MODELLING UNCERTAINTY IN PROBABILISTIC ANALYSIS

4.1 GENERAL

The general definition of the Level 2 limit state function in the TWI software FORM/ MONTE is illustrated in Fig.10. This may be stated as:

$$z = x - y \qquad [1]$$

failure when: $z <= 0$
stable when: $z > 0$

Extending this definition to include modelling uncertainty (M_u based on R-r) gives

$$z = x + M_u - y \qquad [2]$$

Equations [1] and [2] were already implemented in the FORM/MONTE program. The statistical distributions discussed in the preceding section were entered for M_u in order to perform the probabilistic analyses.

4.2 APPLICATION TO TYPICAL EXAMPLES

A number of calculations were carried out using input data selected to investigate the sensitivity of results in different regions of the FAD. In general the input data are typical of welded components, but they were chosen such that deterministic assessments based on the mean property values lay in the three main regions of the FAD. Table 4 summarises the input data used for these analyses. It is noted that relatively high toughness values are selected in order to bias failure towards plastic collapse while lower values are used for fracture-dominated assessments. The reverse trend is noted with respect to tensile properties. In the middle (elastic-plastic) region intermediate values of fracture toughness and tensile properties are used.

In general cov's of 10% were adopted for most variables. However, a slightly higher cov of 20% was adopted for fracture toughness and flaw depth to reflect the fact that higher uncertainties tend to be associated with these two variables.

For each case considered, three failure probability (P_f) calculations were carried out using FORM. First, P_f was evaluated without any allowance for modelling uncertainty (M_u), then a second calculation included the uncertainty associated with the specific region. Finally, a third calculation is performed using M_u derived from the combined data (including all regions). The results of the analyses are given in Table 5 for the K-based calculations. This shows a reduction in failure probability due to the inclusion of modelling uncertainty. However, the reduction in P_f is in general small, typically less than one order of magnitude, except when using the appropriate M_u for the elastic fracture region, where an order of magnitude reduction was obtained.

For the elastic-plastic and plastic collapse regions, there was little difference between the results obtained from the region-specific uncertainty distribution and those based on a general weighted model covering all FAD regions. Overall, it seems reasonable to adopt the modelling uncertainty derived from the combined data (e.g. Weibull {location = -0.06, scale = 0.97, shape = 1.11} for the K-based approach) in probabilistic analyses. This is appropriate because a region-specific model is only likely to give a significantly different result in only one region and also because it is not always known which failure mode is going to be dominant.

4.3 APPLICATION OVER A WIDE RANGE OF FAILURE PROBABILITY ESTIMATES

Further probabilistic analyses were conducted to investigate the effect of modelling uncertainty (M_u) over a wide range of failure probability estimates. This aspect of the work was dictated by the fact that the target failure probabilities considered in the Draft BSI 7910:1999 are in the range 2.3×10^{-1} to 1×10^{-5}. It was therefore desired to investigate the effect of M_u within this range. The basic input data of Table 4 (elastic-region) was adopted in the analyses with the failure probability values varied in the required range by assuming a range of fracture toughness mean values. The general modelling uncertainty distribution (i.e. Weibull {location = -0.06, scale = 0.97, shape = 1.11}) was used in the analysis of these further cases and the results are given in Table 6. Again this shows only a slight reduction in

P_f over the entire range of P_f values considered and suggests a consistent effect of modelling uncertainty.

5. DISCUSSION

5.1 GENERAL TREND IN RESULTS

Overall, it may be stated that the effect of modelling uncertainty in the FAD is to reduce the failure probability estimates slightly, typically by less than one order of magnitude. It is thought that one reason for not having a more significant effect on the failure probability estimates is the large amount of scatter obtained in the validation tests. In effect, the benefit of adopting a limit state based on actual failure points lying predominantly outside the FAD is to a large effect cancelled out by the amount of scatter in these actual failures. The amount of the scatter is evident in the relatively high standard deviation values given in Table 2 and 3.

The present work was based on the Level 2 FAD of BSI PD6493:1991. Mainly because most of the results of the validation study were conducted to demonstrate the conservatism in the Level 2 FAD. However, this FAD has now been dropped from the latest version of the Draft BS 7910 just released (April 1999). There is therefore a need to extend the work to the old default level 3 (now termed Level 2A in BS 7910) FAD. Analyses based on the Level 2A FAD are likely to produce similar results to those obtained in the elastic region, but may be slightly different in the knee and collapse regions.

5.2 POTENTIAL EFFECTS ON BS 7910 FAILURE PROBABILITIES AND PSF'S

Modelling uncertainty on failure probability was found in this study to reduce the failure probability estimates only slightly. It is therefore likely that the current BS 7910 partial safety factors (PSF’s) would, in most cases, not be significantly changed by including modelling uncertainty in the probabilistic fracture mechanics calculations. However, the PSF’s were derived using the default Level 3 (now Level 2A) FAD and it is not at this stage clear if modelling uncertainty would have a greater effect when considered with this FAD. Also, an examination of the current partial safety factors (Table K2, Annex K) in the Draft BS 7910[3] suggests that PSF’s could be significantly different for small differences in target failure probabilities (e.g. from 6.75 at $7x10^{-5}$ to 10 at $1x10^{-5}$).

Overall, it could be stated that the present PSF’s correspond to slightly lower failure probabilities than the stated target values. It is also thought that whilst in most cases, including modelling uncertainty would lead to substantially similar PSF’s as the current ones, there may be merit in a re-analysis to derive new PSF’s particularly for the lowest target failure probabilities (i.e. $7x10^{-5}$ and $1x10^{-5}$).

On the wider use of probabilistic fracture mechanics, it would be appropriate to include modelling uncertainty in the probabilistic model. The general uncertainty model based on R-r (i.e. Weibull {location = -0.06, scale = 0.97, shape = 1.11}for the K-based approach) should be adequate for most purposes. Where there is confidence regarding the dominant region of the FAD, then the appropriate model for that region may be used.

6. CONCLUSIONS

Statistical analysis of an extensive database of large-scale validation data was carried out to derive the distribution of the modelling uncertainty associated with the Level 2 FAD. These were then incorporated into probabilistic analyses using typical example calculations. The following main conclusions are drawn:

- The margin of safety and hence the modelling uncertainty varies around the failure assessment diagram (FAD) with the highest margin in the elastic region and the minimum around the knee (i.e. elastic-plastic) region. However, the data is characterised by a large amount of scatter.

- The Weibull and loge-normal distributions were found to fit the modelling uncertainty (M_u) well, when described in terms of the difference in radial distances from the assessment point and failure line to the FAD origin.

- Including the modelling uncertainty in the probabilistic fracture mechanics calculation in general reduced the failure probability (P_f) estimate slightly; typically this was less than by one order of magnitude. For the elastic region, where the highest margins were observed, P_f was reduced by about one order of magnitude.

- From the reduction observed in failure probability estimates, it may be stated that the current PSF's in the Draft BS 7910 correspond to slightly lower target failure probabilities than the specified values.

- In general, the current Draft BSI 7910 partial safety factors (PSF's) are unlikely to be significantly changed by including modelling uncertainty in the probabilistic fracture mechanics calculations. However, there may be merit in a re-analysis to derive new PSF's particularly for the lowest target failure probabilities (e.g. $7x10^{-5}$ and $1x10^{-5}$).

- The statistical distributions derived in this study may be included in probabilistic analyses provided that the limit state equation has been formulated in terms of differences in radial distance from the FAD origin.

7. REFERENCES

1 BSI PD6493:1991
Guidance on methods for assessing the acceptability of flaws in fusion welded structures
British Standards Institution
London, 1991

2 BS 7910:1999 (Draft)
Guide on methods for assessing the acceptability of flaws in fusion welded structures
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London, April 1999

3 CHALLENGER N V, PHAAL R AND GARWOOD S J
Appraisal of PD 6493:1991 fracture assessment procedures
Part I-III, TWI Report 512/1995
June 1995.

Table 1
Typical results of statistical analysis of validation data using the TWI software DISTFIT (R-r data modified by adding 0.06 to give all positive data before distribution fitting): 0 to 30° data

Distribution	Parameters			Kolmogrov Stat. D*
	Location	Scale	Shape	
Normal	0.83	0.77	-	1.39
Log_enormal	0.0	-0.57	0.90	0.64
Weibull	0.0	0.89	1.18	0.89
Exponential	0.0	0.83	1.00	0.75

Table 2
Results of statistical analysis of K-based validation data in terms of R-r

FAD region	Best-fit Distr.	*Parameters			Moments	
		Location	Scale	Shape	Mean	Std. Dev
Elastic (θ =60-90°)	Weibull	-0.06	1.90	2.13	1.62	0.83
Elastic-plastic (θ =30-60°)	Weibull	-0.06	0.55	1.08	0.47	0.49
Collapse (θ =0-30°)	†Exponential	-0.06	0.83	1.00	0.77	0.83
All (θ =0-90°)	Weibull	-0.06	0.97	1.11	0.87	0.84

* The minimum (R-r) value was -0.054, so 0.06 was added to all values before calculating the scale and shape parameters; the location parameter was fixed at -0.06.

† This is the second best fit after the Log_enormal distribution; exponential distribution was selected because the reliability program (FORM/MONTE) does not recognise a three-parameter log-normal distribution

Table 3
Results of statistical analysis of CTOD-based validation data in terms of R-r

FAD Region	Best-fit Distr.	*Parameters			Moments	
		Location	Scale	Shape	Mean	Std. Dev
Elastic (θ =60-90°)	Log_e-normal	-0.12	0.44	0.63	1.77	1.33
Elastic-plastic (θ =30-60°)	Log_e-normal	-0.12	-0.51	0.72	0.66	0.65
Collapse (θ =0-30°)	Log_e-normal	-0.12	-0.87	0.49	0.35	0.25
All (θ =0-90°)	Log_e-normal	-0.12	-0.37	0.81	0.84	0.92

* The minimum (R-r) value was -0.115, so 0.12 was added to all values before calculating the scale and shape parameters; the location parameter was fixed at -0.12.

Table 4 Basic input data for probabilistic analyses

FAD Region	1	2	3
Dominant failure mode	Elastic fracture (θ = 60-90°)	Elastic-plastic (θ = 30-60°)	Plastic collapse (θ = 0-30°)
Geometry			
Thickness	60	25	15
Width	1000	1000	100
Stresses			
Primary membrane			
Distribution	Normal	Normal	Normal
Mean	90	250	240
Cov	0.10	0.10	0.10
Residual stress			
Distribution	Normal	Normal	Normal
Mean	379	379	180
Cov	0.10	0.10	0.10
Material Properties			
Yield strength (N/mm^2)			
Distribution	Normal	Normal	Normal
Mean	550	450	300
Cov	0.10	0.10	0.10
Tensile strength (N/mm^2)			
Distribution	Normal	Normal	Normal
Mean	660	540	360
Cov	0.10	0.10	0.10
Fracture toughness, K_{mat} ($N/mm^{3/2}$)			
Distribution	Weibull	Weibull	Weibull
Mean	2200	4000	7500
Cov	0.2	0.2	0.2
Location parameter	0.0	0.0	0.0
Scale parameter	2375.9	4319.7	8099.5
Shape parameter	5.83	5.83	5.83
Flaw size / details			
Type	Semi-ellip.	Semi-ellip.	Semi-ellip.
Depth, a (mm)			
Distribution	Normal	Normal	Normal
Mean	2.0	2.0	2.0
Cov	0.20	0.20	0.20
½ length, c (mm)			
Distribution	Normal	Normal	Normal
Mean	20	20	20
Cov	0.0	0.0	0.0

Table 5 Effect of modelling uncertainty on failure probability estimates

FAD Region*	Failure probability, P_f		
	No modelling uncertainty (M_u =0)	*Region specific uncertainty	General uncertainty
1 (Fracture dominated)	5.94E-2	1.61E-3	1.53E-2
2 (Elastic-Plastic)	1.06E-2	4.40E-3	2.72E-3
3 (Collapse dominated)	2.35E-2	5.16E-3†	3.73E-3†

† Results from MONTE, analyses using FORM did not converge

Table 6 Effect of M_u Over a Wide Range of Failure Probability Estimates (Basic input data from Table 4, Region 1; variation with mean K)

*Mean fracture toughness, $N/mm^{3/2}$ Cov = 20%	Failure probability, P_f	
	No modelling uncertainty (M_u =0)	General uncertainty model
1500 (Scale = 1620)	3.90E-1	1.00E-1
2000 (scale = 2160)	9.95E-2	2.55E-2
2200 (scale = 2376)	5.94E-2	1.53E-2
3000 (scale = 3240)	1.03E-2	2.74E-3
4000 (scale = 4320)	1.95E-3	5.30E-4
5000 (scale = 5400)	5.34E-4	9.69E-5†
6000 (scale = 6480)	1.85E-4	3.14E-5†
7000 (scale = 7560)	7.55E-5	1.48E-5†
8000 (scale = 8640)	3.47E-5	5.99E-6†

Cov is coefficient of variation

* Weibull distribution assumed with location parameter = 0 and shape parameter = 5.83

† Results from MONTE, analyses using FORM did not converge

Fig. 1 K-based validation data

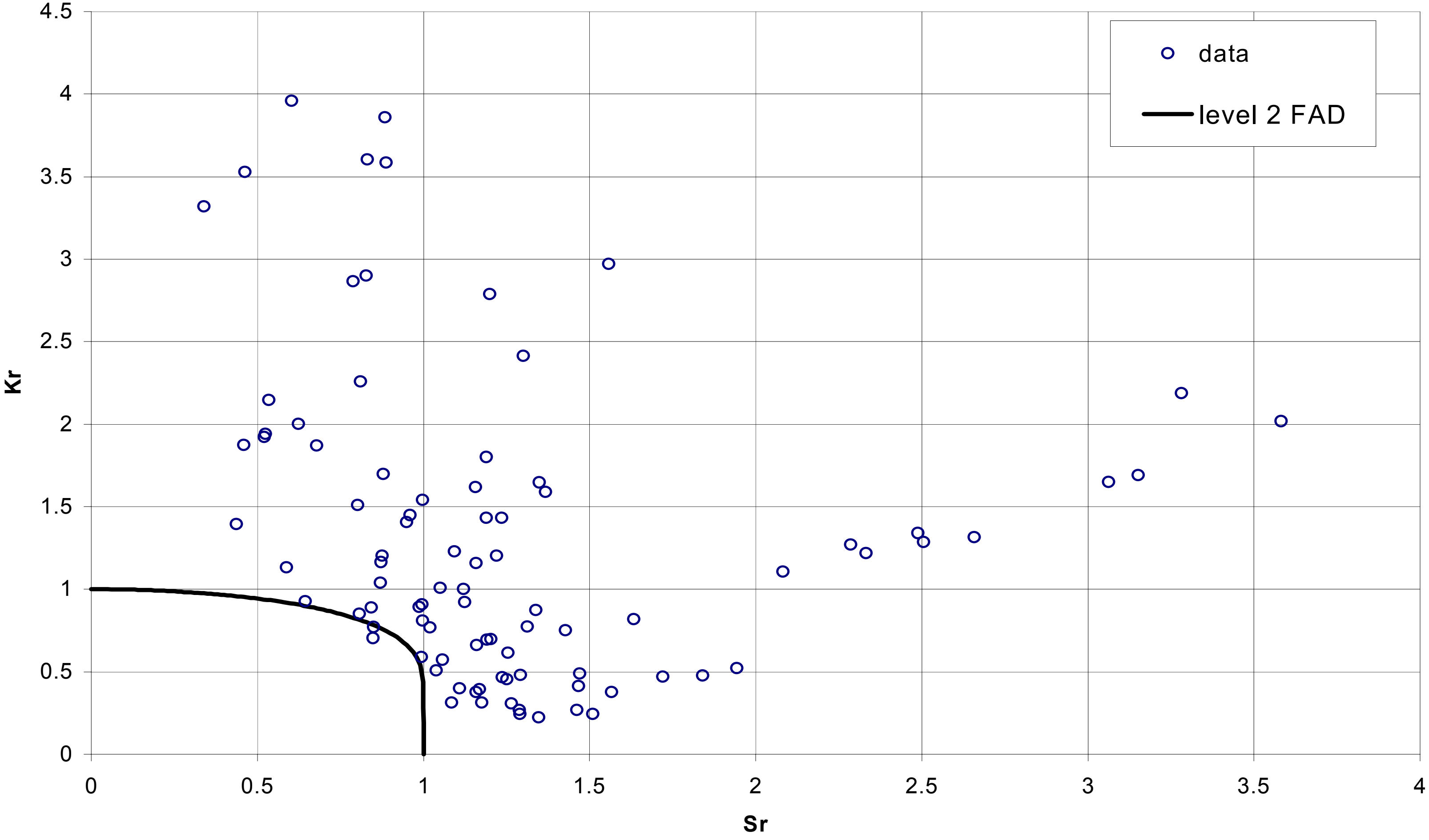


Fig. 2 CTOD-based validation data

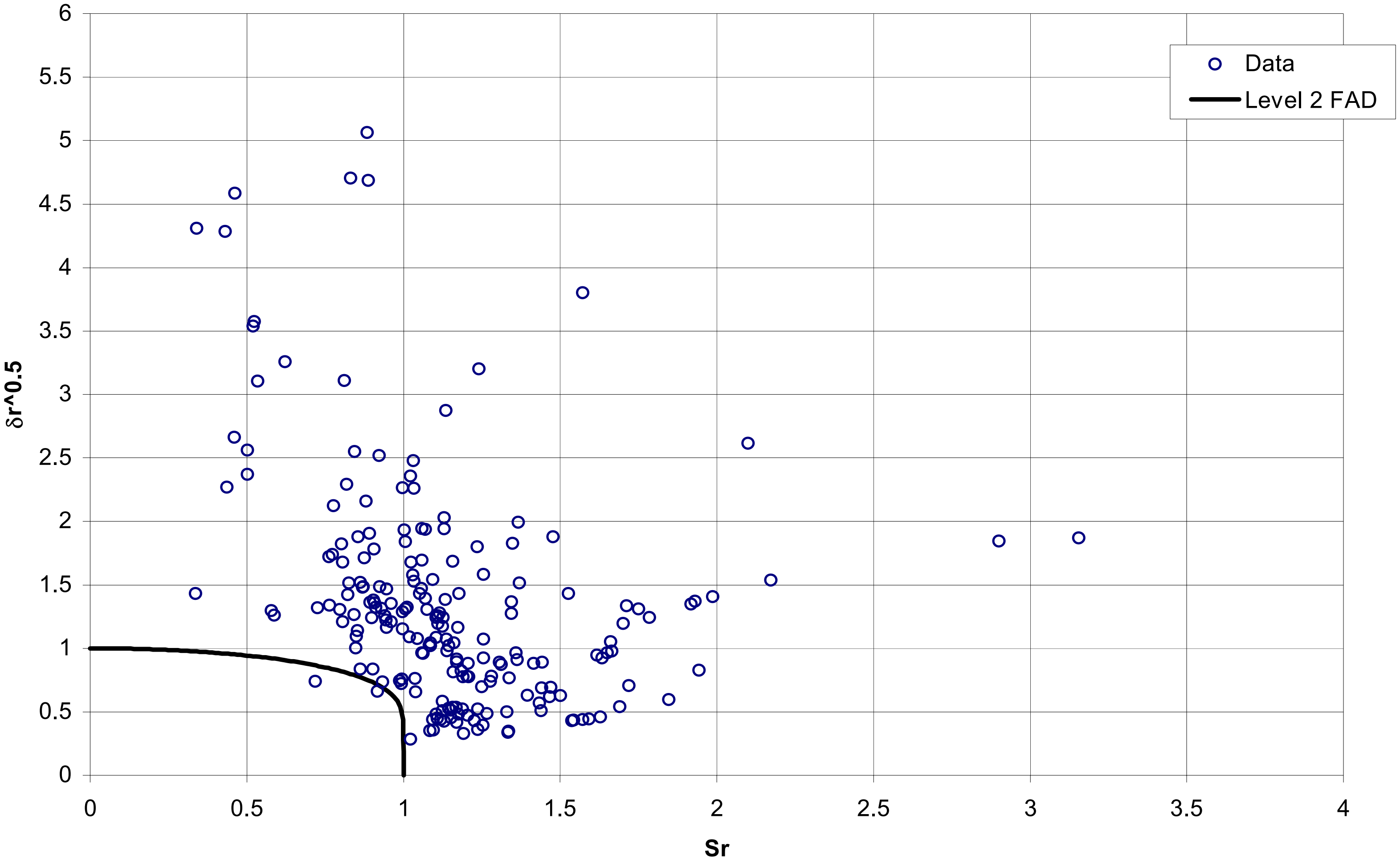


Fig. 3 Illustration of undertainty in failure assessment diagram (FAD)

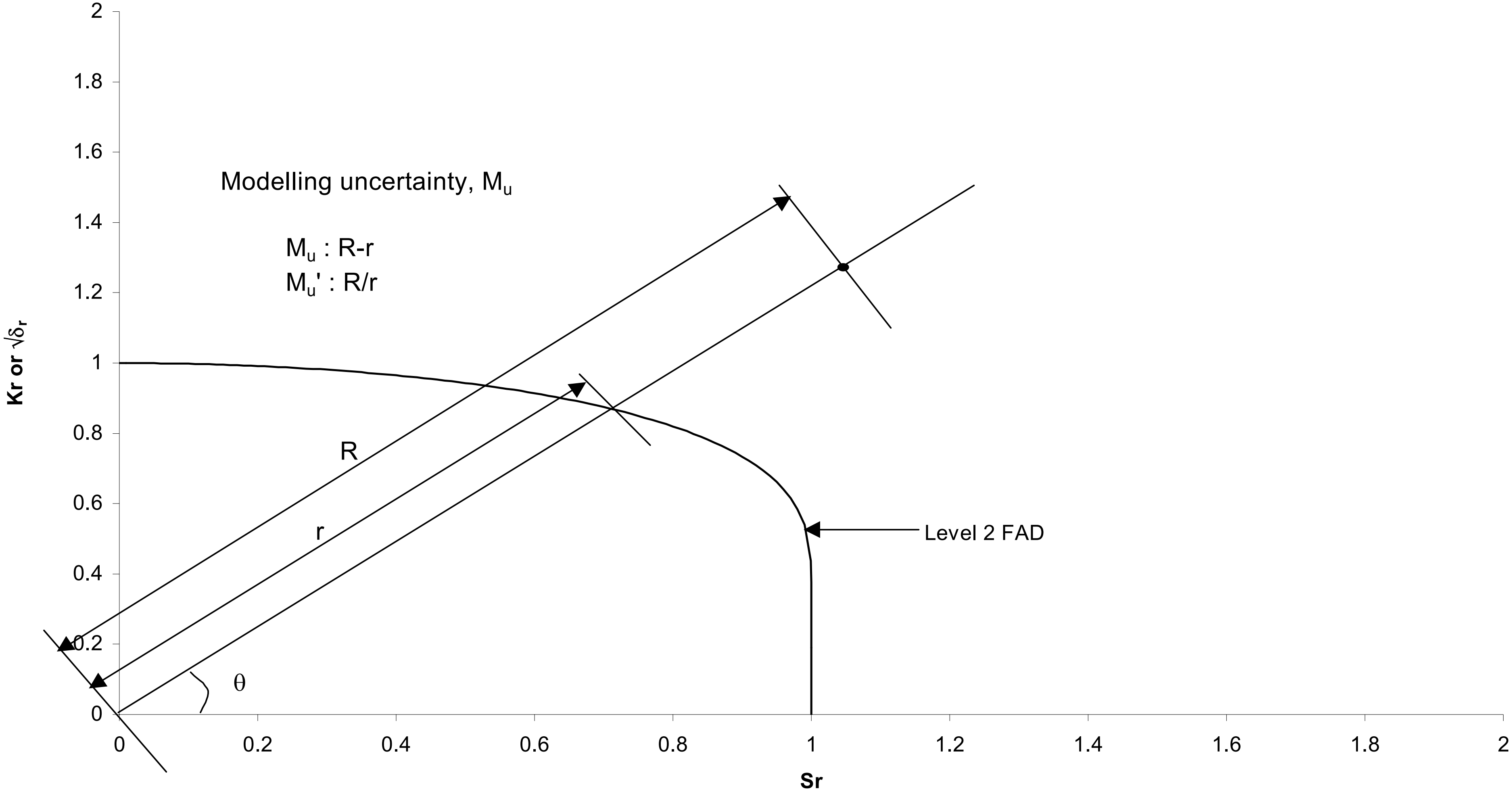


Fig. 4 Variation of modelling uncertainty (M_u = R-r) with theta (K-based data)

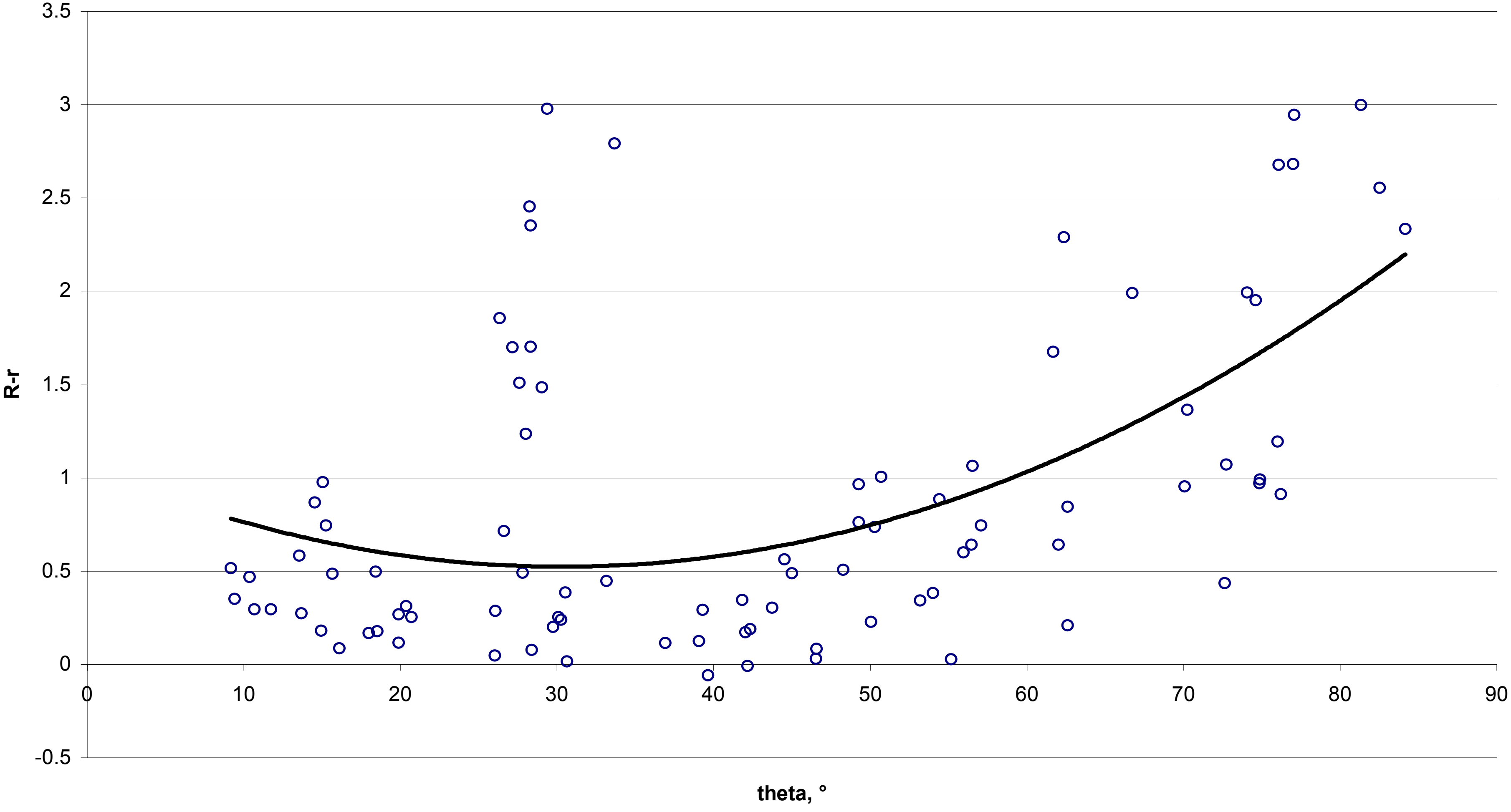


Fig. 5 Variation of modelling uncertainty ($M_u' = R/r$) with theta (K-based data)

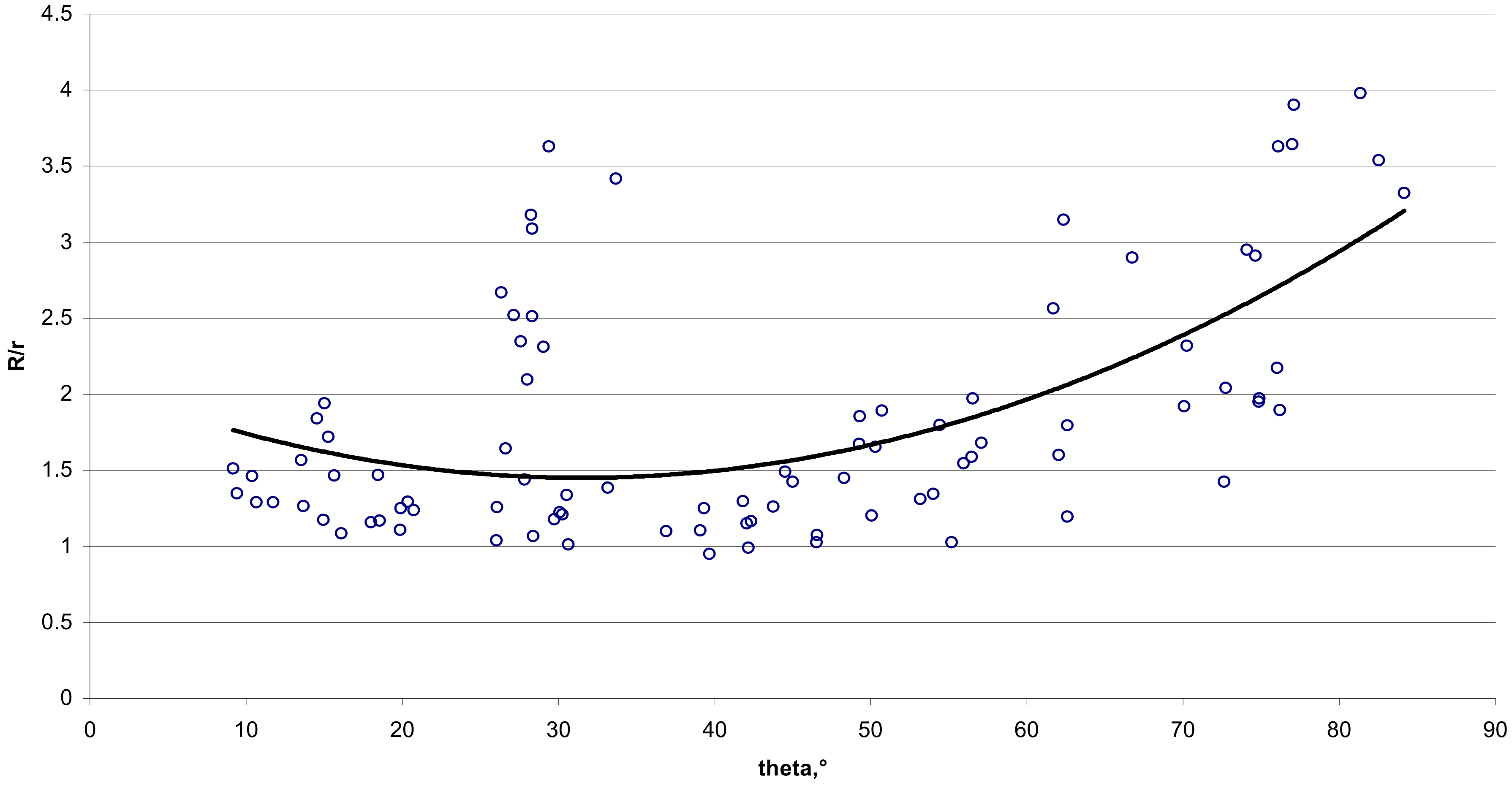


Fig. 6 **Variation of modelling uncertainty (M_u = R-r) with theta** (CTOD-based data)

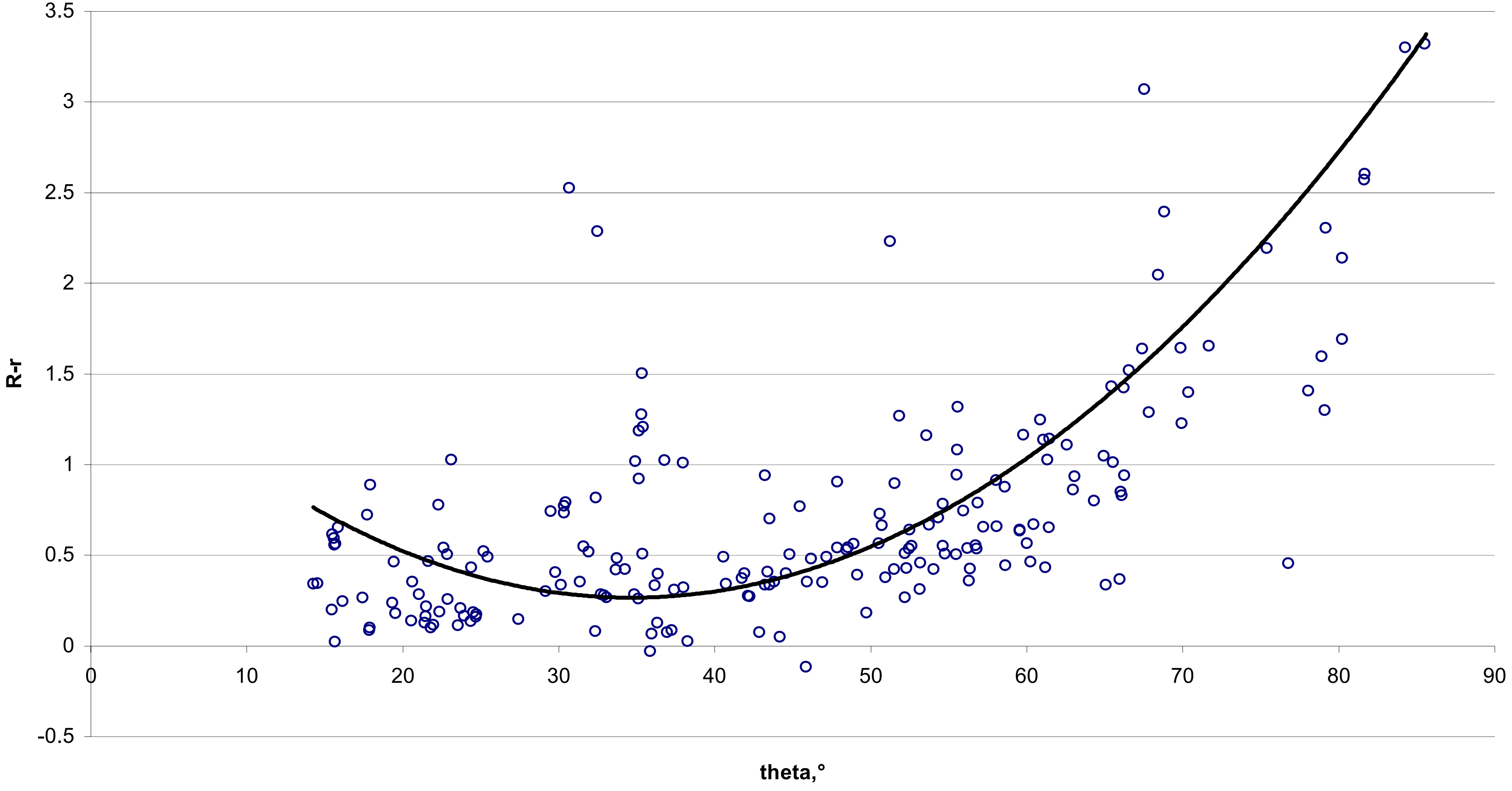


Fig. 7 Variation of modelling uncertainty (M_u' = R/r) with theta (CTOD-based data)

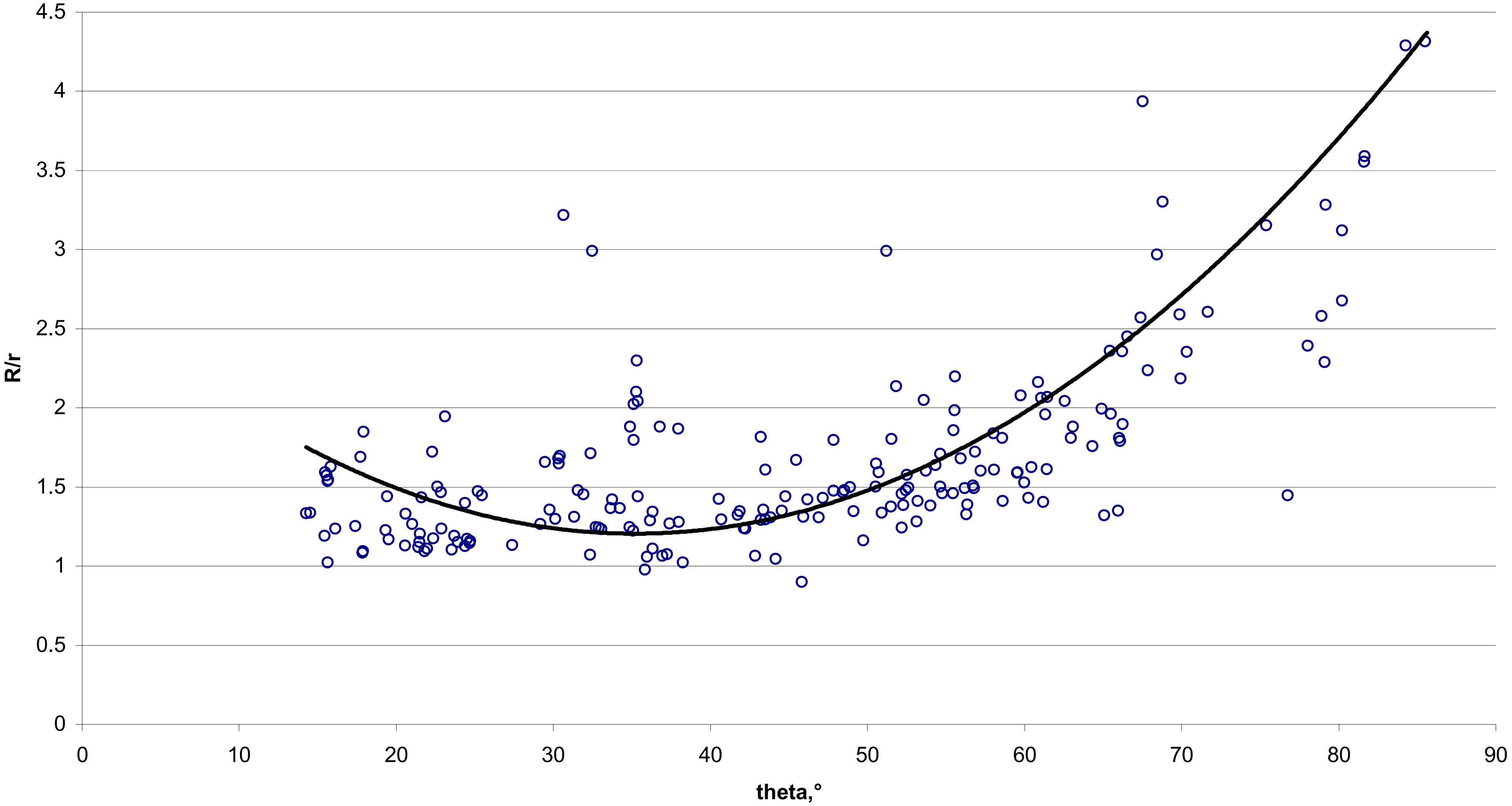


Fig. 8 Spread of validation data over FAD regions

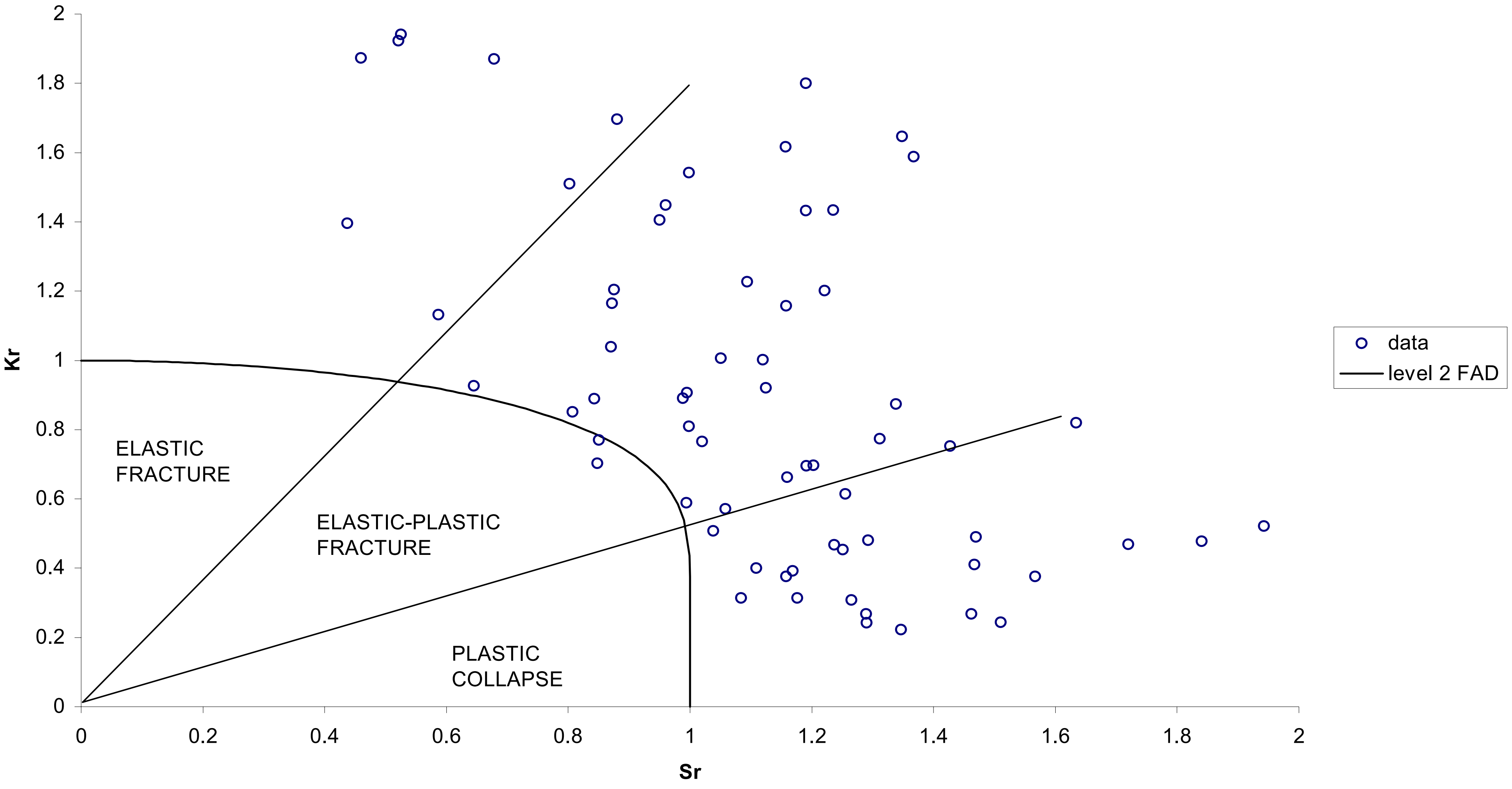


Fig. 9 : Typical overview probability plots obtained from MINITAB

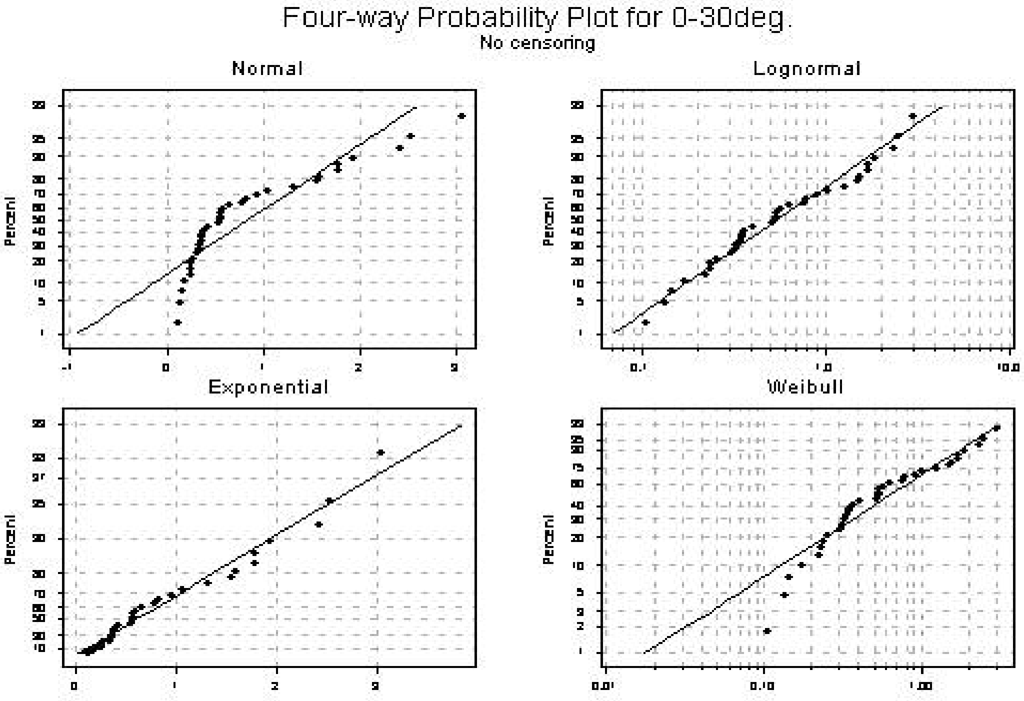
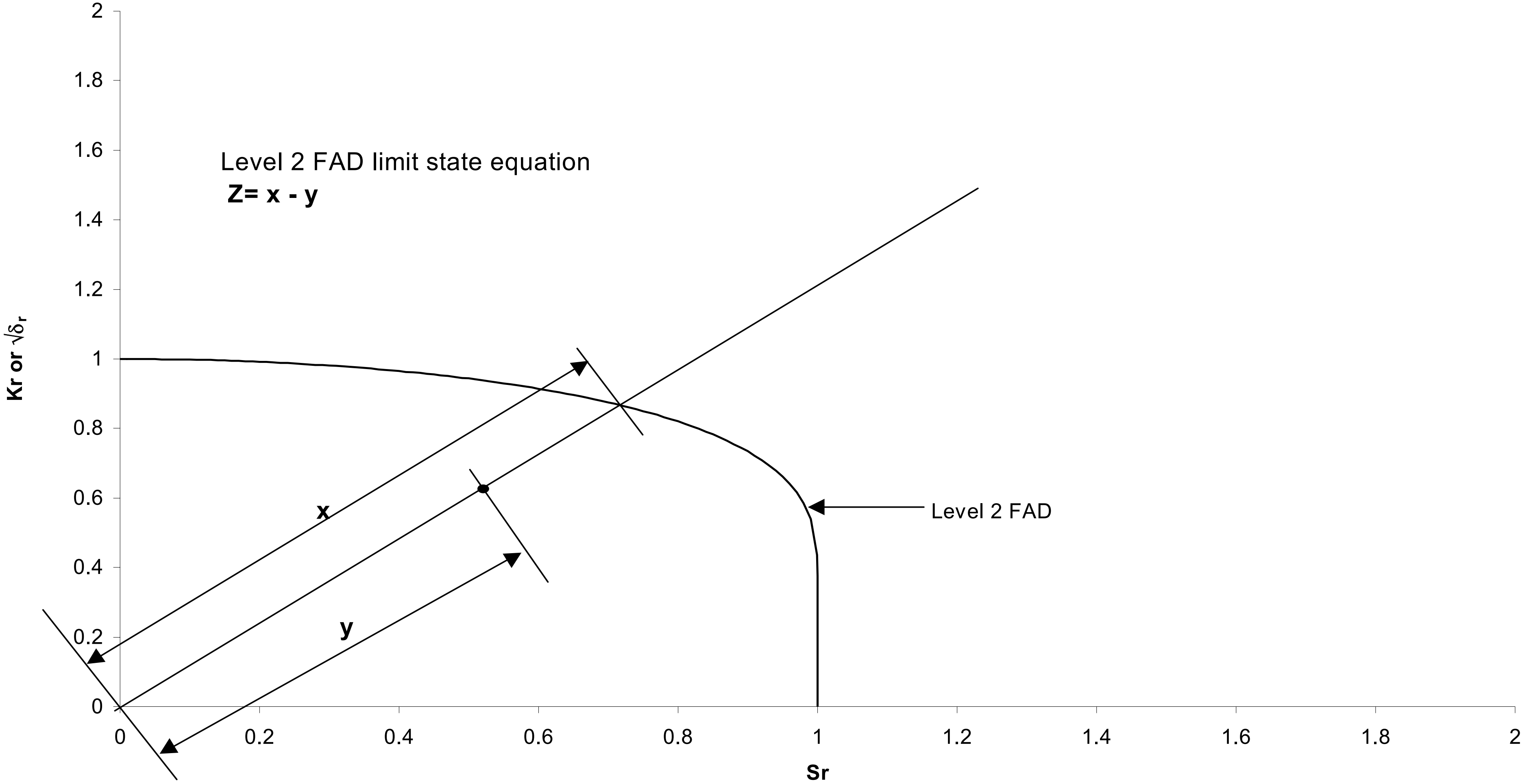


Fig. 10 Definition of limit state function for the Level 2 FAD



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