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Ascertaining Shearer Design Plan Based on Quantization of Weight of Multiple Attributes

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Abstract: To eliminate the instability in deciding upon shearer design plans and take into full account of relevancy among shearers' attributes, the authors propose a way to ascertain the weight of multiple attributes on the basis of sensitivity analysis. With this method, one can work out a matrix through 3-level quantization criteria to compare attributes and then sort design plans accordingly; with interrelationship constraint of multiple attributes, one can obtain the variation range of weight of these attributes that has no impact on the ranking of design plans and identify the significant attribute so as to reach the optimal plan. This method has been proven feasible and practical through sorting the overall performance of design plans of the whole shearer and 6 torque-axis unload grooves in the cutting unit of a shearer.

Keywords: Shearer design plan, Weight of attributes, Sensitivity analysis.

1. INTRODUCTION

The selection of design plan of a shear has impact on its design & development cycle and its market performance. Factors involved in selecting a design plan of a shear include weight and values of attributes, such as thickness of coal seam, maximum coal-cutting height, traction and cutting power [1-3]. Domestic and foreign experts have made great efforts on the attributes involved in shearer design [4-6] and yet, there is no special account in related literature about relevance among attributes, which has significant impact on the selection of shearer design plans. Therefore the authors categorize multiple attributes of shearers into independent attributes and relevant ones, and analyze and identify the significant attributes under constraint conditions, and in this way aid designers to obtain more reasonable shearer design plans.

2. SENSITIVITY ANALYSIS ON WEIGHT OF MULTIPLE ATTRIBUTES OF A SHEARER

Measuring the relative significance of various indicators of a shearer depends largely on the weight of multiple attributes and has impact on the selection of shearer design plan. That the structure and working conditions of a shearer and the ideas of design experts tend to change as time goes, resulting in the change of the significance of each attribute and altering the rank of design results. Thus, it is necessary to quantize multiple attributes to determine the shearer design plan.

2.1. Ascertaining the Weight of Multiple Attributes of Shearer

When it comes to ascertain the weight of attributes, subject method and objective method [7, 8] are used. Given the vital importance of experts' experience and expertise in designing a shearer, it is imperative to bring them in when determining the weight of attributes. Now that there are differences in experts' research fields and their understanding over attributes, the authors of this paper compare the priority of attributes through 3-level quantitative criteria and build up a comparison matrix of attributes. In case attribute q_1 is more important than attribute q_2, then $e_{12} = 1$ and $e_{21} = -1$. Take a shearer's attributes for example. For reliability q_k and traction velocity q_q, in case $q_k \succ q_q$, then $e_{kq} = 1$, $e_{qk} = -1$. If attribute q_1 is as important as q_2, then $e_{12} = e_{21} = 0$ [9].

The procedure to ascertain a shearer's multiple attributes is as follows:

Step 1: Get the comparison matrix E based on the method mentioned above:

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix}$$

Step 2: Construct transfer matrix S for E according to the theory of optimal transfer matrix:

$$S = \begin{bmatrix} \frac{1}{n}(e_{11} + e_{12} + \cdots + e_{1n} + e_{11} + e_{12} + \cdots + e_{1n}) \\ \frac{1}{n}(e_{11} + e_{12} + \cdots + e_{1n} + e_{21} + e_{22} + \cdots + e_{2n}) \\ \vdots \\ \frac{1}{n}(e_{11} + e_{12} + \cdots + e_{1n} + e_{n1} + e_{n2} + \cdots + e_{nn}) \end{bmatrix}$$

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$$
\begin{matrix}
\frac{1}{n}(e_{11}+e_{12}+\cdots+e_{1n}+e_{12}+e_{22}+\cdots+e_{n2}) & \cdots \\
\frac{1}{n}(e_{12}+e_{22}+\cdots+e_{n2}+e_{12}+e_{22}+\cdots+e_{n2}) & \cdots \\
\vdots & \ddots \\
\frac{1}{n}(e_{n2}+e_{n2}+\cdots+e_{nn}+e_{1n}+e_{2n}+\cdots+e_{nn} & \cdots
\end{matrix}
$$

$$
\left.\begin{matrix}
\frac{1}{n}(e_{11}+e_{12}+\cdots+e_{1n}+e_{12}+e_{22}+\cdots+e_{nn}) \\
\frac{1}{n}(e_{21}+e_{22}+\cdots+e_{2n}+e_{12}+e_{22}+\cdots+e_{nn}) \\
\vdots \\
\frac{1}{n}(e_{n1}+e_{n2}+\cdots+e_{nn}+e_{1n}+e_{2n}+\cdots+e_{nn}
\end{matrix}\right]
$$

From which judgment matrix $C=(c_{ij})_{n\times n}$ is obtained, in which

$$c_{ij}=\exp(s_{ij})$$

$$s_{ij}=\frac{1}{n}\sum_{k=1}^{n}(e_{ik}+e_{kj})$$

Step 3: calculate weighted values [10]

$$\omega_j=\omega_j^* \Big/ \sum_{j=1}^{n}\omega_j^*,$$

In which $\omega_j^*=\sum_{i=1}^{n}c_{ji}$, $j=1,2\cdots n$, $\sum_{j=1}^{n}\omega_j=1$.

2.2. Ascertaining Evaluation Values of Shearer Design Plans

Assume: there are m shearer design plans available, represented as $p_1, p_2, \ldots p_m$,and n evaluation indicators, including thickness of coal seam, maximum coal-cutting height, traction and cutting power, etc. represented as $q_1, q_2, \ldots q_n$, and decision matrix of attribute evaluation value a_{ij}:

$$
A=\begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \cdots & a_{mn}
\end{bmatrix}
$$

Since there are discrepancies in the connotation, dimension and order of magnitude of shearer attributes. For example, two attributes of a common shearer like its cutting power which is usually 100~1000kW and its cutting height which is 1~10m in most cases, vary greatly from one another. To eliminate such discrepancy, the authors here normalize matrix A with membership in fuzzy math's and build up membership matrix R:

$$
R=\begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & r_{22} & \cdots & r_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix}
$$

In which, $r_{ij}=\dfrac{a_{ij}-\min\limits_j a_{ij}}{\max\limits_j a_{ij}-\min\limits_j a_{ij}}$ (values of r_{ij} are in direct proportion to attribute sensibility) or $r_{ij}=\dfrac{\max\limits_j a_{ij}-a_{ij}}{\max\limits_j a_{ij}-\min\limits_j a_{ij}}$ (values of r_{ij} are in indirect proportion to attribute sensibility).

The comprehensive evaluation values of each design plan are $M_i=\sum_{j=1}^{n}\omega_j \bullet r_{ij}$, $i=1,2\cdots m$. Then, the priority order p_1', p_2', ... p_m' of these design plans can be determined according to these values.

2.3. Sensitivity Analysis on Weight of Multiple Attributes

Given the multiple attributes involved in shearer design, such as thickness of coal seam, maximum coal-cutting height, traction and cutting power, some of them are independent of one another, while most of them are correlated. For example, there is little relevance between a shearer's cutting depth and its cutting height, while there is great correlation between traction velocity and traction power. Thus, we will conduct independent analysis for attributes with little or no relevance to simplify the process and co relational analysis for attributes with strong correlation to avoid major discrepancies from the actual weight changes. According to the above-mentioned order p_1', p_2', ... p_m' of design plans, R is, as a result, modified as follows:

$$
R'=\begin{bmatrix}
r_{11}' & r_{12}' & \cdots & r_{1n}' \\
r_{21}' & r_{22}' & \cdots & r_{2n}' \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1}' & r_{m2}' & \cdots & r_{mn}'
\end{bmatrix}=\begin{bmatrix}
r_1' \\ r_2' \\ \vdots \\ r_m'
\end{bmatrix}
$$

, from which we can get priority matrix of multiple attributes:

$$
R^*=\begin{bmatrix}
r_1'-r_2' \\
r_1'-r_3' \\
\vdots \\
r_1'-r_m' \\
r_2'-r_3' \\
\vdots \\
r_2'-r_m' \\
\vdots \\
r_i'-r_{i+1}' \\
\vdots \\
r_i'-r_m' \\
\vdots \\
r_{m-1}'-r_m'
\end{bmatrix}
$$

Table 1. Raw data of preliminary shearer design plans.

Attribute	Max Cutting Power (kw)	Max Traction Power (kw)	Max Traction Velocity (kw)	Max Cutting Depth (mm)	Reliability	Sensitivity
1	750	110	21	865	6	9
2	400	55	15	800	6	9
3	1000	120	12.9	865	6	7
4	650	110	20	800	7	5
5	500	60	12.8	800	5	6
6	800	20	22.6	865	5	8

Satisfying the condition $R^* \bullet W^T > 0$, in which, $W^T = (\omega_1, \omega_2, \cdots \omega_n)^T$, $\sum_{j=1}^{n} \omega_j = 1$ $\omega_j \in [0,1]$.

when attributes of a shearer are independent of one another, the variation range of weight ω_j to keep the priority order unchanged is: $\overline{\omega}_j = \left[\overline{\omega}_{j\min}, \overline{\omega}_{j\max}\right]$, $j = 1,2 \cdots n$, whose restraint is:

$$\begin{cases} R^* \bullet W^T > 0 \\ \sum_{i=1}^{n} \omega_i = 1 \\ 0 \le \omega_i \le 1, i = 1,2 \cdots n \end{cases}$$

to facilitate parameter setting, relevance among shear attributes can be resolved to the following two categories:

(a) When two attributes maintain stable relevant priority, the ratio of their weights stays unchanged, i.e. $\frac{\omega_i}{\omega_j} = \frac{\omega_i'}{\omega_j'} = c_1$, in which ω_i , ω_j are original attribute weights and ω_i' , ω_j' are attribute weights after the change in work conditions of the shear or the designer's idea, and c_1=constant.

(b) Define the evaluation set of shear attributes as $Q = \{q_1, q_2, \cdots q_n\}$ and according to the features of relevant attributes in shear design, modify it to $Q = \{Q_1, Q_2, \cdots Q_l\}$, in which Q_l is the l^{th} subset of Q . If, after the change of the order of design plans, the weight of the *j*th attribute in Q_l meets $\sum_{Q_l} \omega_j = \sum_{Q_l} \omega_j' = c_2$, in which ω_j and ω_j' represent the modified attribute weights, and c_2 is a constant, then c_2 is the weight coefficient of the subset of Q_l .

When correlation among attributes is taken into account in weight sensitivity analysis, add the condition $\frac{\omega_i}{\omega_j} = \frac{\omega_i'}{\omega_j'} = c_1$, $\sum_{Q_l} \omega_j = \sum_{Q_l} \omega_j' = c_2$ into restraint conditions of independent attributes and turn the restraint to

$$\begin{cases} R^* \bullet W^T > 0 \\ \sum_{i=1}^{n} \omega_i = 1 \\ 0 \le \omega_i \le 1, i = 1,2 \cdots n \\ \frac{\omega_i}{\omega_j} = c_1 \\ \sum_{Q} \omega_l = c_2 \end{cases}$$

In which, Q is attribute evaluation set and ω_l is the attribute weight of the l^{th} subset in attribute evaluation set Q.

3. CASE STUDY

3.1. Case 1

Sort six preliminary shearer design plans according to their overall performance in six indicators as of max cutting power, max traction power, max traction velocity, max cutting depth, reliability and sensitivity (shown in Table **1**), and identify the important attributes.

Step 1: From Table **1**, we can obtain the following feature matrix A of evaluation indicators of six preliminary shearer design plans.

$$A = \begin{bmatrix} 750 & 110 & 21 & 865 & 6 & 9 \\ 400 & 55 & 15 & 800 & 6 & 9 \\ 1000 & 120 & 12.9 & 865 & 6 & 7 \\ 650 & 110 & 20 & 800 & 7 & 5 \\ 500 & 60 & 12.8 & 800 & 5 & 6 \\ 800 & 20 & 22.6 & 865 & 5 & 8 \end{bmatrix}$$

Step 2: Obtain comparison matrix E according to the correlation of max cutting power, max traction power, max traction velocity, max cutting depth, reliability and sensitivity.

$$E = \begin{bmatrix} 0 & 1 & -1 & 1 & -1 & -1 \\ -1 & 0 & -1 & -1 & -1 & -1 \\ 1 & 1 & 0 & 0 & -1 & -1 \\ -1 & 1 & 0 & 0 & -1 & -1 \\ 1 & 1 & 1 & 1 & 0 & -1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Calculate attribute weight W,

$$W = \left[0.1218, 0.0626, 0.1439, 0.1031, 0.2373, 0.3312\right]^T$$

Step 3: Eliminate the discrepancies among different dimensions of attributes with standardized membership matrix R of feature matrix A.

$$R = \begin{bmatrix} 0.5833 & 0.90 & 0.8367 & 1 & 0.5 & 1.00 \\ 0.0000 & 0.35 & 0.2244 & 0 & 0.0 & 1.00 \\ 1.0000 & 1.00 & 0.0102 & 1 & 1.0 & 0.50 \\ 0.4167 & 0.90 & 0.7347 & 0 & 0.50 & 0.00 \\ 0.1667 & 0.40 & 0.0000 & 0 & 0.75 & 0.25 \\ 0.6667 & 0.00 & 1.0000 & 1 & 0.75 & 0.75 \end{bmatrix}$$

Work out the comprehensive evaluation values of preliminary shearer design plans

$$R \bullet W = \left[0.8007, 1.1121, 0.5991, 0.8385, 0.3061, 0.7546\right]^T,$$

from which we can get the rank of comprehensive evaluation values of preliminary plans, i.e. $M_2 > M_4 > M_1 > M_6 > M_3 > M_5$. According to this, we can get

$$R^* = \begin{bmatrix} -0.5833 & -0.55 & -0.6123 & -1 & -0.5 & 0.00 \\ -1.0000 & -0.65 & 0.1224 & -1 & -1 & 0.50 \\ -0.4167 & -0.55 & -0.5103 & 0 & -0.5 & 1 \\ -0.1667 & -0.05 & 0.2244 & 0 & -0.75 & 0.75 \\ -0.6667 & 0.35 & -0.7756 & -1 & -0.75 & 0.25 \\ -0.1666 & 0 & -0.102 & -1 & 0 & -1 \\ -0.5833 & -0.1 & 0.7245 & -1 & -0.5 & -0.5 \\ 0.25 & 0.5 & 0.7347 & 0 & -0.25 & -0.25 \\ -0.25 & 0.9 & -0.2653 & -1 & -0.25 & -0.75 \\ -0.4167 & -0.1 & 0.8265 & 0 & -0.5 & 0.5 \\ 0.4166 & 0.5 & 0.8367 & 1 & -0.25 & -0.25 \\ -0.0834 & 0.9 & -0.1633 & 0 & -0.25 & -0.25 \\ -0.3333 & -1 & 0.9898 & 0 & -0.25 & 0.25 \\ 0.5 & -0.4 & 1 & 1 & 0 & 0.5 \\ 0.8333 & 0.6 & 0.0102 & 1 & 0.25 & 0.25 \end{bmatrix}$$

Step 4: With attributes being uncorrelated, we can get the variation range of attribute weight that can maintain the priority order of design plans unchanged, as shown in Table **2**.

Table 2. Weight range of uncorrelated attributes.

	Attribute	Weight	Weight Range
1	Max Cutting Power	0.1218	0—0.4023
2	Max Traction Power	0.0626	0—0.3333
3	Max Traction Velocity	0.1439	0—0.5548
4	Max Cutting Depth	0.1031	0—0.5048
5	Reliability	0.2373	0—0.5
6	Sensitivity	0.3312	0.1061—0.5

Table 3. Weight ranges of correlated attributes.

	Attribute	Weight	Weight Range
1	Max Cutting Power	0.1218	0—0.2412
2	Max Traction Power	0.0626	0.0623—0.33
3	Max Traction Velocity	0.1439	0—0.2677
4	Max Cutting Depth	0.1031	0—0.3031
5	Reliability	0.2373	0.1715—0.3350
6	Sensitivity	0.3312	0.1715—0.3350

It can be seen from the table that range lengths of various attributes vary from one another and the biggest range of max traction velocity indicates its weakest sensitivity and vice versa. Weight ranges of attribute 1 to 5 all start from 0, while that of sensitivity cannot start from 0, which indicates the priority of sensitivity is higher than that of other attributes, and therefore one should be discreet when it comes to value attribute 6.

Step 5: analyze the correlation of attributes in shearer design: (1) traction power and traction velocity are closely related to each other, and thus categorize max traction power and max traction velocity into a subclass, with weight coefficient being 1/3, and restraint condition being $\omega_2 + \omega_3 = 1/3$; (2) a shearer's high reliability indicates that its parts and the whole machine are of longer failure-free operation duration and lower failure rate; high sensitivity indicates a shearer is of better mobility and maneuverability. If these two attributes are of equal priority, then the relative priority coefficient of reliability to sensitivity is 1, restraint condition $\frac{\omega_5}{\omega_6} = 1$, and the attribute weight ranges that keep the rank of design plans unchanged is as shown in Table **3**.

It can be seen from Table **3** that attribute weight ranges have changed to maintain the rank of design plan unchanged. Ranges of reliability and sensitivity have the smallest change, which indicates they are the most sensitive; that the

Table 4. Data Sheet of Preliminary Plans.

Attribute	Groove Depth (mm)	Groove-root Width (mm)	Coefficient of Processing Difficulty	Tensile Strength (*MPa*)	Reliability	Fracture Sensitivity
1	8	8	0.7	980	6	9
2	8	16	0.4	980	7	8
3	8	2	0.6	980	5	6
4	8	16	0.4	885	7	7
5	8	2	0.6	885	5	9
6	8	8	0.7	885	6	6

Table 5. Independent attribute weight range.

	Attribute	Weight	Weight Range
1	Groove Depth	0.1312	0—0.4175
2	Groove-root Width	0.0671	0—0.3134
3	Coefficient of Processing Difficulty	0.1457	0—0.5735
4	Tensile Strength	0.1101	0—0.5051
5	Reliability	0.2403	0—0.52
6	Fracture Sensitivity	0.3400	0.1102—0.510

beginning value of weight ranges of attribute 2 and 5 change from zero to a non-zero value which indicates the priority of max traction power, reliability and sensitivity is higher than that of other attributes. Thus, one should be discreet when it comes to fix values for these three attributes.

3.2. Case 2

3.2.1. Experiment Plan and Data

Take for example the torque-axis unload groove in the cutting unit of MG750/1800-WD shearer. The unload groove is designed to protect the transmission system and motor through instant fracture when overload happens. Sort the overall performance of six preliminary design plans based on six indicators (i.e. fracture torque value, groove-root width, coefficient of processing difficulty, material tensile strength, reliability and fracture sensitivity; some of them are shown in Table **4**) of attributes of the torque-axis unload groove in the cutting unit of a shearer, and identify the important attributes. Groove 1 is a 40Cr- trapezoidal groove, Groove 2 a 40Cr- U-shaped groove, Groove 3 a 40Cr- V-shaped groove, Groove 4 a 20CrMo- U-shaped groove, Groove 5 a 20CrMo- V-shaped groove and Groove 6 a 20CrMo- trapezoidal groove.

We can find decision matrix A from Table **5**.

$$A=\begin{bmatrix} 8 & 8 & 0.7 & 980 & 6 & 9 \\ 8 & 16 & 0.4 & 980 & 7 & 8 \\ 8 & 2 & 0.6 & 980 & 5 & 6 \\ 8 & 16 & 0.4 & 885 & 7 & 7 \\ 8 & 2 & 0.6 & 885 & 5 & 9 \\ 8 & 8 & 0.7 & 885 & 6 & 6 \end{bmatrix}$$

Through calculation, we can get weight ranges of independent attributes as shown in Table **5** and those of correlated attributes in Table **6**.

It can be seen from Table **6** that attribute weight ranges have changed to maintain the rank of design plan unchanged. Ranges of reliability and sensitivity have the smallest change, which indicates they are the most sensitive; that the beginning value of weight ranges of attribute 1, 4 and 5 change from zero to a non-zero value indicates the priority of groove depth, reliability and fracture sensitivity is higher than that of other attributes. Thus, the values of these three attributes should be discreetly chosen when feature matrix A is identified.

Table 6. Weight ranges of correlated attributes.

	Attribute	Weight	Weight Range
1	Groove Depth	0.1312	0.06150—0.2430
2	Groove-root Width	0.0671	0—0.341
3	Coefficient of Processing Difficulty	0.1457	0—0.2702
4	Tensile Strength	0.1101	0.1045—0.3111
5	Reliability	0.2403	0.1697—0.3403
6	Fracture Sensitivity	0.3400	0.1697—0.3403

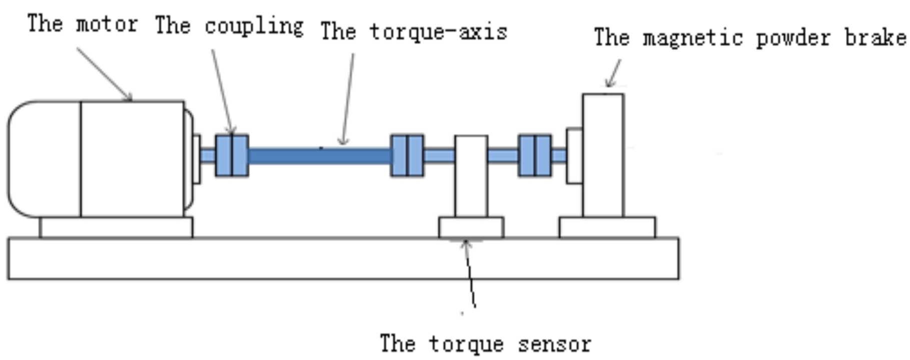

Fig. (1). The test platform structure.

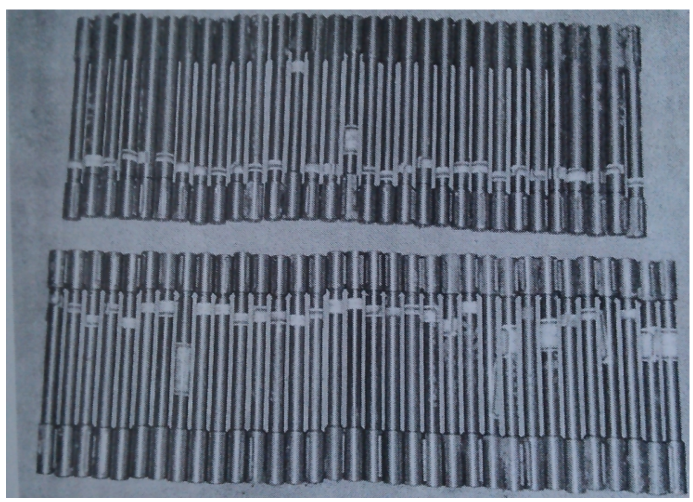

Fig. (2). A photo of test torque axis.

3.2.2. Result Comparison

We design a special test platform to verify the accuracy of the rank of preliminary torque-axis design plans obtained from the above-mentioned method. The test platform is made up of a motor, a frequency converter, a torque sensor, a magnetic particle brake and a magnetic particle brake controller, as shown in Fig. (**1**). The converter can slowly start the motor to reach the set resolution speed, the torque sensor can continuously collect torque and velocity signals and the magnetic brake can produce the set torque output through its controller. Torque axes used in the test will be made with the same material and in the same structure and diminished proportionally to 1/3 of the sizes of the original axes. 10 test pieces will be processed for Plans 1,2,4 and 6; 12 test pieces will be processed for Plans 3 and 5. As it is known from the table of preliminary plans that Plans 3 and 5 are of poor reliability, two spare test pieces are made (as shown in Fig. **2**).

Test data are shown in Fig. (**3**), in which horizontal axis represents the number of test torque piece and vertical axis represents the multiplying rate of load at the moment of fracture. 1-10 represent test torque pieces of Plan 1 and they fracture under about 1.5 times of the rating load; 11-20 rep-

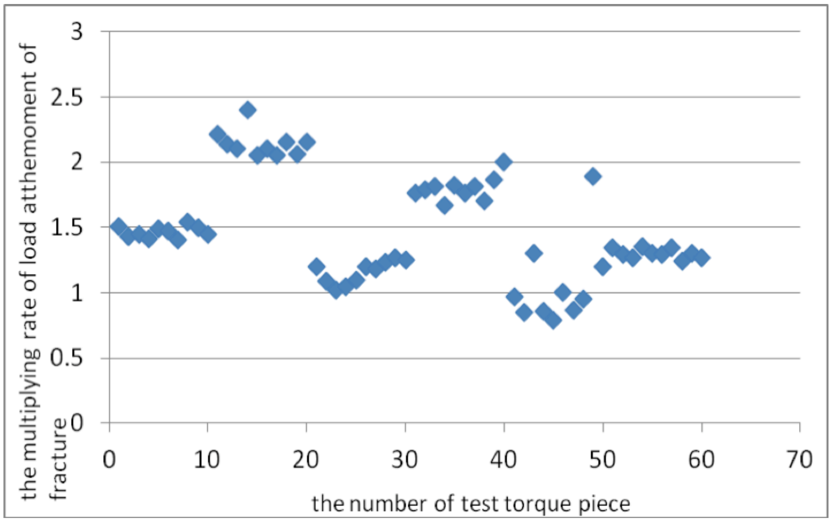

Fig. (3). Test data.

resent test torque pieces of Plan 2 and they fracture under about 2.2 times of the rating load; 21-30 represent test torque pieces of Plan 3 and they fracture under about 1.2 times of the rating load; 31-40 represent test torque pieces of Plan 4 and they fracture under about 1.75 times of the rating load; 41-50 represent test torque pieces of Plan 5 and they fracture under about 0.9 times of the rating load; 51-60 represent test torque pieces of Plan 6 and they fracture under about 1.4 times of the rating load. The plan order obtained from test results is basically in agreement with that from the above-mentioned method.

CONCLUSION

In this paper, an algorithm to analyze the sensitivity of a shearer's multiple attributes is proposed to provide designers and decision-makers with quantified theoretical basis, in which the authors offer restraint conditions for independent and correlated attributes respectively, find out the attributes with higher sensitivity and thus obtain the attributes with relative higher priority.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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