Re-analyzing the mechanical properties of corroded steel bar based on similarity measure

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Abstract

In this paper, the records of steel bar mechanical behavior that are similar to condition-specific data are sifted from the corroded steel bar database based on a similarity measure method. The similarity of mechanical behavior between the corroded steel bar database and the corroded steel samples under certain conditions are analyzed by the similarity measure S . The sifted records can be used for linear regression analysis and combined with limited condition-specific data to obtain a larger coefficient of determination R^2 as there are more similar steel bar corrosion characteristics that are relevant to the condition-specific data. It is found that nearly all of the sifted records in the database share the same certain conditions which are similar to the condition-specific data.

Keywords Steel bar · Corrosion · Mechanical behavior · Condition-specific · Similarity measure

1 Introduction

The corrosion of steel bar in reinforced concrete (RC) structures can cause serious deterioration to load-bearing capacity [1]. The mechanism of steel bar corrosion is strongly related to aggressive ion (such as chloride ion) attacks and concrete carbonation [2]. Corrosion of steel bar results in a loss of area and the uncertain degradation of mechanical behaviors, leading to loss of structural bearing capacity. Various studies have been conducted to evaluate the effects of reinforcement corrosion on the reliability of RC structures [3–7] to ensure structural safety. However, as such studies are highly dependent on empirical models of steel bar mechanical property deterioration and derived from limited data in particular situations, these models have limited applications.

Due to the problems inherent to such research, numerous experimental tests have since been conducted on the mechanical behavior of steel bar, considering the

corrosion effects. Two different sources of corroded steel bar specimens exist: one occurs in structures that are corrosion damaged by different aggressive agents such as chloride and carbonation and the other is accelerate artificial corrosion caused by such methods as impressed-current, soaking in acid solution, and wet-drying. As it is difficult and time-consuming to obtain naturally corroded steel bar, naturally corroded specimens are limited to only a small quantity in published literature.

Test results of reinforcements using natural corrosion and artificial corrosion have shown that the tensile behavior of corroded steel bar is seriously degraded. As the number of tested specimens has been limited in different reported cases, the largest amount of published steel bar behavior data under various corrosion conditions is collected in this study to statistically analyze the degradation of the corroded steel bar. However, as the data contains mixed samples from different corrosion conditions, there will be a large coefficient of variation, limiting the

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engineering applicability of the statistical results. Therefore, a re-analysis of these data is urgently required, as well as an investigation into corrosion effects on mechanical behavior.

Numerous research papers have explored the processing methods of data similarity. The process of a number of such studies has been to construct multivariate probability distribution of clay parameters, sift the clay parameters with a larger coefficient of variation from a database based on a Bayesian approach for calculating the similarity between site-specific geotechnical data and a database, and constructing a more applicable transformation relationship model [8, 9].

In the present work, condition-specific data and database for naturally and artificially accelerated corroded steel bars were established according to different corrosion situations. A similarity measure method was proposed and applied to the above condition-specific data and database. By application of similarity measure method, corroded steel bars sharing similar performance degradation to the condition-specific data were sifted from the established corroded steel bar database. Finally, the corrosion condition and linear regression parameters of corroded steel bars before and after sifting were analyzed and discussed.

2 Database versus condition-specific data

The application of the similarity measure method is composed of condition-specific data and a database. Condition-specific data is the tensile behavior of the corroded steel bars under certain conditions. The database typically contains a wider range of conditions than those with a single condition. In this paper, the data of the tensile behavior of corroded steel bars was collected from reported tests, and the collected data was divided into two groups of naturally and artificially accelerated corroded steel bars

according to the different corrosion situations detailed in Tables 1 and 2. The tensile behavior parameters of the corroded steel bars contain yield strength, ultimate strength, ratio of ultimate strength to yield strength, and the elongation of steel bar.

2.1 Database

Table 1 shows the collected reported test results of nine published paper concerning the tensile behavior of naturally corroded steel bars. The corroded steel bars with steel bar type HRB335 collected from Ref [10, 12, 13, 15, 16, 18] were located in the atmospheric zone, while the corroded steel bars with type HRB335 collected from Ref. [14, 19] and the corroded steel bars with type BSt420S collected from Ref. [17] were located in the marine zone. The data of the eight Ref. [12–19] regarding naturally corroded steel bars were selected as the naturally corroded steel bars database, while the data of Ref. [10] was selected as corresponding condition-specific data. The selected data with reference number, steel bar type, specimen number, standard value, and environmental condition is provided in Table 1. Due to the variedide the condition-specific data for tensile behavior of the naturally and artificially corroded steel bar, respectivel strengths and lack of tensile behavior of the intact steel bars in the collected dataset, the mechanical behavior of the corroded steel bars was normalized with respect to the standard value of the mechanical behavior of the steel bar specimens. The dimensionless yield strength is defined as the yield strength of the corroded steel bar samples, divided by the standard value of the yield strength. The dimensionless ratio of ultimate strength to yield strength is defined as the actual values of the ratio of ultimate strength to the yield strength, divided by the standard values of the ratio of ultimate strength to yield strength. The dimensionless ultimate strength and dimensionless elongation are also

Table 1 Collected naturally corroded steel bar database with reference number, steel bar type, specimen number, and site condition

Ref. No.	Steel bar type	Specimen number	Standard value			Site condition
			Yield strength	Ultimate strength	Elongation (%)	
[10]	HRB335	34	335	455	17	Atmospheric
[12]	HRB335	3	335	455	17	Atmospheric
[13]	HRB335	55	335	455	17	Atmospheric
[14]	HRB335	27	335	455	17	Marine
[15]	HRB335	4	335	455	17	Atmospheric
[16]	HRB335	39	335	455	17	Atmospheric
[17]	BSt420S	10	420	500	10	Marine
[18]	HRB335	43	335	455	17	Atmospheric
[19]	HRB335	29	335	455	17	Marine

Table 2 Collected artificial corroded steel bar database with reference number, steel bar type, specimen number, and corrosion condition

Ref. No.	Steel bar type	Specimen number	Standard value			Corrosion condition
			Yield strength	Ultimate strength	Elongation (%)	
[11]	HRB335	23	335	455	17	Electrical
[12]	HRB335	4	335	455	17	Electrical
[20]	HRB335	21	335	455	17	Electrical
[21]	B500C	8	500	575	7.50	Chloride salt spray
[22]	B500SD	35	500	575	16	Electrical
[23]	B500SD	85	500	575	16	Electrical
[24]	B500SD	72	500	575	16	Electrical
[25]	HRB400	31	400	540	16	Electrical; wetting and drying
[26]	Grade 420	47	420	620	9	Electrical
[27]	Grade 420	39	420	620	9	Electrical
[28]	A706	29	420	550	14	Electrical
[29]	Grade 420	7	420	500	10	Chloride salt spray
[30]	B500SD	58	500	575	16	Electrical

divided by the standard value of ultimate strength and elongation, respectively.

The natural corroded steel bar database consisted of 210 records for four dimensionless tensile behavior parameters. The 4 dimensionless tensile behavior parameters are denoted by $(X_1^n, X_2^n, \dots, X_4^n)$ and the i -th ($i = 1, 2, \dots, 210$) records in the naturally corroded steel bars database are denoted by $(X_{1i}^n, X_{2i}^n, \dots, X_{4i}^n)$, where X_1 is the dimensionless yield strength, X_2 is the dimensionless ultimate strength, X_3 is the dimensionless ratio of ultimate strength to yield strength, and X_4 is the dimensionless elongation. In this paper, the superscript “n” denotes the naturally corroded specimens, while “a” denotes the artificially corroded specimens. Table 2 shows the collected reported test results of thirteen published papers regarding the tensile behavior of the artificially corroded steel bars. The corroded steel bars with steel bar type HRB335, B500SD, Grade 420, and A706 that were artificially corroded by electrical current were collected from Ref. [11, 12, 20], [22–24, 30], [26, 27] and [28], respectively. The corroded steel bars accelerated corroded by chloride salt spray with type B500C and Grade 420 were collected from Ref. [21] and [29], respectively. The corroded steel bars with type HRB400 that were accelerated corroded by electrical technology under a wetting and drying cycle were collected from Ref. [25]. The twelve Ref. [12, 20–30] on artificially corroded steel bars were compiled using the artificial accelerated corrosion steel

bar database consisting of 436 records. While corroded steel bars from Ref. [11] was selected as condition-specific artificial corrosion steel bar data. The four dimensionless tensile behaviors are denoted by $(X_1^a, X_2^a, \dots, X_4^a)$, the i -th ($i = 1, 2, \dots, 436$) records in the artificial corroded steel bars database are denoted by $(X_{1i}^a, X_{2i}^a, \dots, X_{4i}^a)$, and the collected data with reference number, steel bar type, specimen number, standard value, and certain condition are also provided in Table 2.

In this study, ribbed steel bars with a minimum standard yield strength of 335 MPa under natural or artificial corrosion were collected for re-analyzing. According to the European Standard EN 10,027–1 [31], the designation of the analyzed steel bars is presented in Table 3. It should be noted that in general, under natural corrosion conditions, steel bars tend to be non-uniform corrosion such as local corrosion and pitting corrosion; while steel bars tend to be uniform corrosion under artificial corrosion conditions.

2.2 Condition-specific data

Tables 4 and 5 provide the condition-specific data for tensile behavior of the naturally and artificially corroded steel bar, respectively. The normalized samples obtained from Figs. 1 to 3 of the Ref. [10] were selected as condition-specific natural corrosion steel bar data, as shown in Table 4, and were obtained from the atmospheric zone.

Table 3 Designation of the analyzed steel bars according to EN 10,027-1

Steel bar type	HRB335	HRB400	BSt420S	B500C	B500SD	A706	Grade420
Designation according to EN 10,027-1	B335C	B400C	B420C	B500C	B500C	B420C	B420C

Table 4 Condition-specific natural corrosion steel bar samples

No.	Corrosion (%)	Condition-specific samples $\underline{X}$			
		X_1^n	X_2^n	X_3^n	X_4^n
1	0.806	1.313	1.384	1.054	1.520
2	1.671	1.231	1.200	0.974	1.441
3	2.016	1.283	1.343	1.046	1.473
4	2.535	1.262	1.343	1.064	1.393
5	2.938	1.335	1.347	1.009	1.271
6	3.053	1.219	1.266	1.039	1.203
7	3.226	1.266	1.311	1.035	1.301
8	3.744	1.197	1.297	1.084	1.464
9	3.571	1.262	1.329	1.053	1.585
10	3.859	1.271	1.338	1.053	1.332
11	4.205	1.262	1.306	1.035	1.302
12	4.954	1.236	1.261	1.020	1.186
13	5.818	1.172	1.283	1.095	1.009
14	6.221	1.167	1.229	1.053	1.242
15	6.048	1.133	1.220	1.077	1.092
16	6.855	1.133	1.202	1.061	1.043
17	9.332	1.025	1.098	1.071	0.908
18	9.908	1.064	1.116	1.049	0.932
19	9.332	0.900	0.915	1.016	0.846
20	10.196	0.784	0.829	1.058	0.792
21	11.521	0.987	1.044	1.058	1.056
22	12.154	1.060	1.097	1.035	1.156
23	12.442	1.017	1.039	1.021	0.928
24	12.730	0.987	1.039	1.053	0.922
25	12.903	0.814	0.940	1.155	0.757
26	14.862	0.927	0.984	1.062	0.801
27	15.611	0.914	0.966	1.057	0.967
28	15.956	0.858	0.890	1.037	0.698
29	16.878	0.819	0.925	1.130	0.772
30	17.569	0.811	0.880	1.086	0.935
31	19.009	0.725	0.799	1.103	0.731
32	19.355	0.772	0.862	1.116	0.820
33	19.758	0.811	0.875	1.079	0.931
34	20.104	0.794	0.844	1.063	0.830

The normalized samples from Figs. 4, 5, and 7 of the Ref. [11] were used as the condition-specific artificial corrosion steel bar data and were obtained from artificially accelerated corrosion with impressed current (electrical). Condition-specific data will be denoted by $\underline{X}$ in the following analysis. This $\underline{X}$ can be visualized as a spreadsheet table of size $(k \times q)$, where $k = 34$ (Table 4) or $k = 23$ (Table 5) is the total number of data points (rows or records) with regard to condition-specific natural corrosion or artificially corroded steel bar data, and $q = 4$ to match the four dimension information available in the database.

Table 5 Condition-specific artificial corrosion steel bar samples

No.	Corrosion (%)	Condition-specific samples $\underline{X}$			
		X_1^a	X_2^a	X_3^a	X_4^a
1	0.000	1.134	1.146	1.011	1.867
2	0.000	1.035	1.078	1.041	1.569
3	2.302	1.092	1.196	1.096	1.326
4	2.558	1.027	1.131	1.102	1.271
5	2.813	1.123	1.226	1.092	1.569
6	6.905	1.075	1.099	1.023	1.192
7	8.696	1.058	1.040	0.983	0.712
8	16.113	0.900	0.939	1.043	0.584
9	17.391	0.833	0.954	1.146	0.614
10	18.670	0.594	0.818	1.379	0.639
11	20.460	0.855	0.907	1.060	0.560
12	24.808	0.830	0.892	1.075	0.365
13	25.320	0.712	0.833	1.170	0.651
14	26.087	0.774	0.768	0.993	0.207
15	31.202	0.571	0.742	1.298	0.438
16	31.714	0.802	0.753	0.940	0.523
17	35.294	0.532	0.638	1.200	0.334
18	39.386	0.459	0.677	1.475	0.450
19	40.154	0.535	0.653	1.221	0.517
20	46.292	0.585	0.594	1.015	0.395
21	46.803	0.397	0.467	1.177	0.201
22	50.895	0.369	0.476	1.291	0.146
23	55.243	0.329	0.331	1.005	0.152

2.3 Multivariate normality

The data points similar to the condition-specific tensile behavior of the corroded steel bars data were sifted from the reinforcement corrosion database based on the similarity measure method. The proposed method operates in the multivariate normal distribution space. In general, the corroded steel bar sample points tend to be normally distributed when the sample point is large enough. In this paper, each dimension $(X_1, X_2, \dots, X_4)$ of the condition-specific sample obeys normal distribution by the Kolmogorov–Smirnov test in Matlab, and fulfills the null hypothesis at the default 5% significance level. Moreover, it is assumed that the condition-specific tensile behavior $\underline{X} = (X_1, X_2, \dots, X_4)$ of the corroded steel bars is multivariate normal distribution [32]. The probability density function (PDF) is:

$$f(\underline{x} | \underline{\mu}_s, C_s) = |C_s|^{-\frac{1}{2}} (2\pi)^{-\frac{q}{2}} \exp \left[-0.5 \times (\underline{x} - \underline{\mu}_s)^T C_s^{-1} (\underline{x} - \underline{\mu}_s) \right] \quad (1)$$

where $f(\underline{x} | \underline{\mu}_s, C_s)$ denotes a multivariate normal PDF for $\underline{x}$ with mean vector $\underline{\mu}_s$ and covariance matrix C_s , $\underline{\mu}_s$ ($\underline{\mu}_s \in \mathbb{R}^{4 \times 1}$) is the mean vector for $\underline{X}$, and C_s ($C_s \in \mathbb{R}^{4 \times 4}$) is

the covariance matrix for $\underline{\mathbf{X}}$ that characterizes the condition-specific correlation among $(\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_4)$.

3 Similarity measure approach

The proposed Similarity measure approach contains two steps. First, the posterior PDF of $\mathbf{X} = (\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_4)$ condition on condition-specific $\underline{\mathbf{X}}$, denoted by $f(\mathbf{x}|\underline{\mathbf{X}})$, where $f(\mathbf{x}|\underline{\mathbf{X}})$, is adopted to quantify the similarity between the database and the condition-specific data $\underline{\mathbf{X}}$. Let $\mathbf{x}^{(i)}$ be the i -th database points ($i = 1, 2, \dots, z$), z is the number of the total database points, $z = 210$ and $z = 436$ match the number of the naturally corroded steel bars database and the artificially corroded steel bars database points, and $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ is the posterior PDF of the i -th database points. In addition, a similarity measure that quantifies the similarity between a database record and the condition-specific data is adopted. Here, $\mathbf{x}^{(i)}$ is the i -th record in the database, and this similarity measure, denoted by $S(\mathbf{x}^{(i)})$, indicates that a record with a larger $S(\mathbf{x}^{(i)})$ is more similar to the condition-specific data. That is, the data points with large $S(\mathbf{x}^{(i)})$ values have a stronger correlation with the tensile performance of condition-specific corroded steel bar samples.

3.1 Construct the PDF $f(\mathbf{x}|\underline{\mathbf{X}})$

The posterior PDF of $\mathbf{X} = (\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_4)$ condition on condition-specific $\underline{\mathbf{X}}$ for quantifying the similarity between the database and the condition-specific data $\underline{\mathbf{X}}$ is as follows:

$$f(\mathbf{x}^{(i)}|\underline{\mathbf{X}}) = |\mathbf{C}_s|^{-\frac{1}{2}} (2\pi)^{-\frac{q}{2}} \exp \left[-0.5 \times (\mathbf{x}^{(i)} - \underline{\boldsymbol{\mu}}_s)^T \mathbf{C}_s^{-1} (\mathbf{x}^{(i)} - \underline{\boldsymbol{\mu}}_s) \right] \quad (2)$$

where $\mathbf{x}^{(i)}$ is the i -th record in the database.

Note that $\mathbf{x}^{(i)}$ is usually an incomplete vector with empty information, and not all records are four dimensions. Thus, the records with incomplete information are represented by $\mathbf{x}_0^{(i)}$. The PDF for such data points can be expressed by:

$$f(\mathbf{x}^{(i)}|\underline{\mathbf{X}}) = |\mathbf{C}_s|^{-\frac{1}{2}} (2\pi)^{-\frac{q_0}{2}} \exp \left[-0.5 \times (\mathbf{x}_0^{(i)} - \underline{\boldsymbol{\mu}}_s)^T \mathbf{C}_s^{-1} (\mathbf{x}_0^{(i)} - \underline{\boldsymbol{\mu}}_s) \right] \quad (3)$$

where q_0 is the dimension of the i -th row record with incomplete information in the database, and $q_0 < q = 4$.

3.2 Compute the similarity measure $S(\mathbf{x}^{(i)})$

The records with large $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ values in the database are more similar to the condition-specific samples; that is, if $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ is larger than $f(\mathbf{x}^{(j)}|\underline{\mathbf{X}})$, the $\mathbf{x}^{(i)}$ record is more similar. However, the collected $\mathbf{x}^{(i)}$ and $\mathbf{x}^{(j)}$ may contain different dimension information, and as a result, $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ and

$f(\mathbf{x}^{(j)}|\underline{\mathbf{X}})$ cannot be directly compared. For example, if the i -th row record $\mathbf{x}^{(i)}$ only contains the 2-dimensional information $(\mathbf{X}_1, \mathbf{X}_2)$, while the j -th row record $\mathbf{x}^{(j)}$ contains the three-dimensional information $(\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3)$, the $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ and $f(\mathbf{x}^{(j)}|\underline{\mathbf{X}})$ cannot be directly compared. However, after normalization using a proper scaling factor [8] α is defined as:

$$\alpha = \int f(\mathbf{x}^{(i)}|\underline{\mathbf{X}}) g(\mathbf{x}^{(i)}) d\mathbf{x}^{(i)} \quad (4)$$

where $g(\mathbf{x})$ is the multivariate normal prior PDF that summarizes the data structure for the database. In Eq. (4), $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ and $g(\mathbf{x}^{(i)})$ are multivariate PDFs with a lower dimension if $\mathbf{x}^{(i)}$ is incomplete, namely $f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})$ and $g(\mathbf{x}^{(i)})$ are 2-dimensional PDFs if $\mathbf{x}^{(i)}$ only contains the $(\mathbf{X}_1, \mathbf{X}_2)$ information. If $g(\mathbf{x})$ is the multivariate PDF of the database, $g(\mathbf{x}^{(i)})$ is the marginal PDF after integrating out the unobserved information dimension. Then $S(\mathbf{x}^{(i)}) = f(\mathbf{x}^{(i)}|\underline{\mathbf{X}})/\alpha$, $S(\mathbf{x}^{(i)})$, and $S(\mathbf{x}^{(j)})$ can be directly compared, and a database record with $S(\mathbf{x}^{(i)}) > 1$ is more similar to the condition-specific data than others in the database. Note that this similarity is based on the similarity of four-dimensional data. Even though the steel bar performance of other dimensions is very similar, if there is one dimension quite different from condition-specific data, it will also very likely be defined as a dissimilar record. The record with $S(\mathbf{x}^{(i)}) > 1$ is defined as a similar record in this paper.

The multivariate normal prior probability density function $g(\mathbf{x})$ of the database must be estimated for the constructed database (described in Sect. 2.1), as well as the natural corrosion steel bar database and artificial corrosion steel bar database. The bootstrapping technique [33] is applied to estimate the mean vector $\underline{\boldsymbol{\mu}}_s$ and the covariance matrix $\mathbf{C}_s$ of the prior PDF $g(\mathbf{x})$. For example, the covariance coefficient σ_{gl}^2 of $(\mathbf{X}_g, \mathbf{X}_l)$ is estimated as follows ($g, l = 1, 2, 3, 4$): m random data points are randomly generated from the database set and m corresponds to the number of records containing the 2-dimensional information $(\mathbf{X}_g, \mathbf{X}_l)$ in the database, as shown in Table 6. Note that "210" represents the number of records in the natural corrosion database, and the content of "()" means the corresponding number of records in the artificial accelerated

Table 6 The numbers m of data points with bivariate information in database

	$\mathbf{X}_1$	$\mathbf{X}_2$	$\mathbf{X}_3$	$\mathbf{X}_4$
$\mathbf{X}_1$	210 (436)	171 (402)	171 (402)	128 (221)
$\mathbf{X}_2$	Symmetry	171 (402)	171 (402)	89 (217)
$\mathbf{X}_3$			171 (402)	89 (217)
$\mathbf{X}_4$				128 (221)

corrosion database. The covariance coefficient is obtained from the m random generated data points, and this is repeated 1000 times to obtain 1000 bootstrap samples of the σ_{gl}^2 estimates. The mean of the 1000 bootstrap samples are then taken as covariance coefficients σ_{gl}^2 . The means vector μ_s is also estimated using the method described above.

3.3 Application of corrosion steel bar sample

The naturally corroded steel bar database and artificially accelerated corroded steel bar database are considered in this paper, as shown in Tables 1 and 2, respectively. The condition-specific data is divided into condition-specific natural corrosion steel bars and condition-specific artificial corrosion steel bars, as shown in Tables 4 and 5, respectively. The database records with similar tensile behavior to the corresponding condition-specific data are sifted by application of similarity measure method. Tables 7 and 8 show the top 20 database records with relatively large $S(\mathbf{x}^{(i)})$, as well as three other records with small $S(\mathbf{x}^{(i)})$. The symbol “-” means that the records contain no information regarding mechanical behavior. Most records with large $S(\mathbf{x}^{(i)})$ have the same condition as the condition-specific

data. The records with different conditions generally have small $S(\mathbf{x}^{(i)})$.

Figure 1a–d show the results for the natural corrosion steel bar database and the corresponding condition-specific data. This represents dimensionless yield strength versus mass loss, dimensionless ultimate strength versus mass loss, dimensionless ratio of ultimate strength to yield strength versus mass loss, and dimensionless elongation versus mass loss, respectively. Results for the artificial corrosion steel bar database and the corresponding condition-specific data are provided in Fig. 2a–d. In these plots, the condition-specific data is plotted as the black solid square, and the corresponding database records with $S(\mathbf{x}^{(i)}) > 1$ are sifted from the database as the similar data and plotted as the red solid symbol. The less similar records with $S(\mathbf{x}^{(i)}) < 1$ are plotted as the blue hollow symbol.

4 Regression analysis

Two regression curves are provided in this work. The first curve is fitted according to the condition-specific data and the sifted records with $S(\mathbf{x}^{(i)}) > 1$ of the corresponding

Table 7 $S(\mathbf{x}^{(i)})$ value for chosen naturally corroded steel bar database records

Rank	$S(\mathbf{x}^{(i)})$	Corrosion (%)	X_1^n	X_2^n	X_3^n	X_4^n	Site condition
1	545.903	17.589	1.050	–	–	0.795	Atmospheric
2	394.166	19.852	1.046	–	–	0.902	Atmospheric
3	57.224	20.185	1.041	–	–	0.729	Atmospheric
4	43.303	16.959	1.054	–	–	0.768	Atmospheric
5	37.140	13.028	1.051	–	–	0.709	Atmospheric
6	12.895	11.526	1.134	1.205	1.063	1.198	Marine
7	8.264	5.713	1.289	1.350	1.047	1.352	Atmospheric
8	5.387	2.429	1.334	1.386	1.039	1.409	Atmospheric
9	4.965	3.763	1.332	1.379	1.036	1.394	Atmospheric
10	4.020	4.139	1.312	1.353	1.031	1.317	Atmospheric
11	3.925	9.352	1.068	1.117	1.045	–	Atmospheric
12	3.920	5.533	1.089	1.144	1.050	–	Marine
13	3.888	0.821	1.059	1.107	1.046	–	Marine
14	3.827	3.694	1.296	1.358	1.048	1.509	Atmospheric
15	3.819	9.168	1.240	1.270	1.024	1.178	Atmospheric
16	3.768	1.847	1.339	1.389	1.037	1.509	Atmospheric
17	3.584	0.616	1.352	1.408	1.041	1.528	Atmospheric
18	3.429	5.581	1.051	1.092	1.039	–	Atmospheric
19	3.080	4.905	1.051	1.131	1.076	–	Atmospheric
20	3.061	4.618	1.309	1.340	1.024	1.336	Atmospheric
Extra records with small S	0.093	7.543	1.151	1.197	1.039	1.560	Marine
	9.656×10^{-8}	3.329	1.136	1.354	1.191	–	Marine
	1.171×10^{-25}	25.420	0.887	0.699	0.788	0.468	Marine

Table 8 $S(\mathbf{x}^{(i)})$ value for chosen artificially corroded steel bar database records

Rank	$S(\mathbf{x}^{(i)})$	Corrosion (%)	$\mathbf{X}_1^a$	$\mathbf{X}_2^a$	$\mathbf{X}_3^a$	$\mathbf{X}_4^a$	Corrosion condition
1	3.513×10^8	22.70	0.751	–	–	–	Electrical
2	3.374×10^8	21.30	0.781	–	–	–	Electrical
3	2.462×10^8	17.10	0.744	–	–	–	Electrical
4	8.765×10^7	18.60	0.731	–	–	–	Electrical
5	7.985×10^7	12.00	0.802	–	–	–	Electrical
6	3.311×10^7	19.90	0.723	–	–	–	Electrical
7	1.497×10^5	13.70	0.842	–	–	–	Electrical
8	1.115×10^5	13.60	0.843	–	–	–	Electrical
9	490.461	12.10	0.865	–	–	–	Electrical
10	69.045	13.20	0.872	–	–	–	Electrical
11	4.526	19.72	0.804	0.846	1.053	–	Electrical
12	4.410	21.43	0.784	0.826	1.054	–	Electrical
13	4.149	19.69	0.757	0.803	1.060	–	Electrical
14	4.128	28.40	0.651	–	–	–	Electrical
15	4.121	16.96	0.833	0.902	1.082	–	Electrical
16	4.103	12.87	0.802	0.878	1.094	–	Electrical
17	4.012	32.30	0.749	0.794	1.059	–	Electrical
18	3.941	17.45	0.816	0.837	1.025	–	Electrical
19	3.746	19.61	0.840	0.856	1.019	–	Electrical
20	3.745	9.73	0.890	0.935	1.050	–	Electrical
Extra records	0.142	13.55	0.852	0.983	1.154	0.448	Chloride salt spray
with small S	4.491×10^{-4}	2.63	1.109	1.173	1.057	2.311	Electrical; wetting and drying
	9.090×10^{-7}	5.18	1.017	1.302	1.280	1.434	Chloride salt spray

database. The other curve is fitted according to the condition-specific data and all records in the database.

4.1 Naturally corroded steel bar

In Fig. 1, the condition-specific data is collected from the tested steel bars in Ref. [10], and obtained from the naturally corroded steel bar in the atmospheric zone. The tested steel bars in Ref. [12, 15, 17] are obtained from the corroded steel bar in a marine environment, as stated in Table 1, and are different from the condition-specific data. The other data is obtained from the atmospheric zone. In addition, there are 14 data points with $S(\mathbf{x}^{(i)})$ greater than 1 that are sifted from Ref. [11], with a total of 55 records, 6 sifted data points from Ref. [12] with a total of 27 records, 5 sifted data points from Ref. [14] with a total of 39 records, 1 sifted data point from Ref. [15] with a total of 10 records, and 14 sifted data points from Ref. [16] with a total of 43 records. No data points were sifted from Ref. [10, 13, 17]. It is then determined that most of the records from the Ref. [12, 15, 17] have $S(\mathbf{x}^{(i)})$ of less than 1, as plotted in Fig. 1, indicating that these records are less similar to condition-specific data.

Figure 1a shows the result of the dimensionless yield strength versus mass loss for the natural corrosion steel bar database and the corresponding condition-specific

data. It can be seen that the dimensionless yield strength decreases considerably with an increase in the corrosion level. The linear regression model for the naturally corroded steel bars based on limited condition-specific data and the sifted similar records, or all the database records before sifting, results in the following equations, respectively:

$$X_{1,a}^n = -2.1340\xi_s + 1.2984 \quad R_a^2 = 0.6146 \quad (5a)$$

$$X_{1,b}^n = -1.3720\xi_s + 1.2280 \quad R_b^2 = 0.3750 \quad (5b)$$

where $\mathbf{X}_1^n$ is the dimensionless yield strength of the natural corrosion steel bar, and $X_{1,a}^n$ and $X_{1,b}^n$ are the dimensionless yield strength of the natural corrosion steel bar after and before sifting, respectively. The same applies in the following analysis below. Additionally, ξ_s is the corrosion level of steel bar and $R^2 \in [0, 1]$ is the coefficient of determination [34]. The closer R^2 is to 1, the greater the degree of linear association between the predictor variable and the response variable. The slope of the linear regression equation derived from the condition-specific data and the records after sifting shows considerable decrease with corrosion level compared to before sifting as the slope changes from -1.3720 to -2.1340 . This result suggests that when the effects of site conditions is not considered

(a) Dimensionless yield strength vs. mass loss

(c) Dimensionless ratio of ultimate strength to yield strength vs. mass loss

(b) Dimensionless ultimate strength vs. mass loss

(d) Dimensionless elongation vs. mass loss

Fig. 1 Natural corrosion of steel bar results using similarity measure method: **a** dimensionless yield strength versus mass loss; **b** dimensionless ultimate strength versus mass loss; **c** dimensionless ratio of

ultimate strength to yield strength versus mass loss; **d** dimensionless elongation versus mass loss

and all sample points are taken into consideration instead, the effect of corrosion on the mechanical property deterioration of steel bars may be underestimated. It should also be noted that the coefficient of determination R^2 after sifting is significantly larger than that before sifting. Additionally, Mean Square Error (MSE) after sifting has different degrees of reduction than before, as shown in Table 9. The MSE is expressed as:

$$\text{MSE} = \frac{1}{n-2} \sum_{i=1}^n (X_i - \hat{X}_i)^2 \quad (6)$$

where n is the number of the sample data points for calculating, X_i is the observed value of the mechanical behavior

of corroded steel bar, and $\hat{X}_i$ is the estimated result of linear regression. The MSE is a measure of the quality of an estimator, and the closer the MSE is to 0, and the better the quality of the estimator is. R_a^2 is the coefficient of determination, and MSE_a is the MSE of regression curve based on the condition-specific data and the sifted similar records from the database. In addition, R_b^2 is the coefficient of determination, and MSE_b is the MSE based on the condition-specific data and all the database records before sifting. The coefficient of determination increases obviously from 0.3750 to 0.6146 while the MSE decreases by 32.61% from 0.01703 to 0.01148.

(a) Dimensionless yield strength vs. mass loss

(c) Dimensionless ratio of ultimate strength to yield strength vs. mass loss

(b) Dimensionless ultimate strength vs. mass loss

(d) Dimensionless elongation vs. mass loss

Fig. 2 Artificial corrosion of steel bar results using similarity measure method: **a** dimensionless yield strength versus mass loss; **b** dimensionless ultimate strength versus mass loss; **c** dimension-

less ratio of ultimate strength to yield strength versus mass loss; **d** dimensionless elongation versus mass loss

Table 9 The coefficient of determination and the mean square error (MSE) results before and after sifting in the database

Corresponding figure	Corrosion type	Relationship model	R_b^2	R_a^2	MSE_b	MSE_a	$\frac{MSE_b - MSE_a}{MSE_b} \times 100\%$ (%)
Figure 1a	Natural	Dimensionless yield strength versus mass loss	0.3750	0.6146	0.01703	0.01148	32.61
Figure 1b	Natural	Dimensionless ultimate strength versus mass loss	0.5614	0.7353	0.01391	0.00791	43.17
Figure 1c	Natural	Dimensionless ratio of ultimate strength to yield strength versus mass loss	0.0643	0.1801	0.00898	0.00070	92.24
Figure 1d	Natural	Dimensionless elongation versus mass loss	0.4050	0.7488	0.07152	0.01847	74.18
Figure 2a	Artificial	Dimensionless yield strength versus mass loss	0.4732	0.6031	0.01029	0.00644	37.43
Figure 2b	Artificial	Dimensionless ultimate strength versus mass loss	0.4624	0.6022	0.01294	0.00665	48.63
Figure 2c	Artificial	Dimensionless ratio of ultimate strength to yield strength versus mass loss	0.0086	0.0985	0.00707	0.00371	47.53
Figure 2d	Artificial	Dimensionless elongation versus mass loss	0.2089	0.4655	0.10516	0.07262	30.95

Figure 1b shows that the dimensionless ultimate strength also decreases considerably with an increase in the mass loss level. The linear regression model for the naturally corroded steel bars after and before sifting is described by the following equations, respectively:

$$X_{2,a}^n = -2.8330\xi_s + 1.3804 \quad R_a^2 = 0.7353 \quad (7a)$$

$$X_{2,b}^n = -1.7120\xi_s + 1.2937 \quad R_b^2 = 0.5614 \quad (7b)$$

where X_2^n is the dimensionless ultimate strength of the natural corrosion steel bar. The slope of the linear regression equation after sifting also shows considerable decrease with corrosion level compared to before sifting as the slope changes from -1.7120 to -2.8330 .

The result of the dimensionless ratio of ultimate strength to yield strength versus mass loss is provided in Fig. 1c. It should be noted that the coefficient of determination has a very slight increasing trend after sifting, however, is still very close to 0. This illustrates that the linear model does not explain any corrosion variation in the dimensionless ratio of ultimate strength to yield strength of its mean.

Figure 1d shows that dimensionless elongation decreases with steel bar mass loss. It should be stated that there is no collected information regarding the dimensionless elongation in Ref. [14]. The linear regression analysis for the naturally corroded steel bars after and before sifting results in the following equations:

$$X_{4,a}^n = -3.7160\xi_s + 1.4675 \quad R_a^2 = 0.7488 \quad (8a)$$

$$X_{4,b}^n = -2.6480\xi_s + 1.3491 \quad R_b^2 = 0.4050 \quad (8b)$$

where X_4^n is the dimensionless elongation of the natural corrosion steel bar. The slope of the linear regression equation derived in the condition-specific data and the records after sifting also show considerable decrease with corrosion level compared to before sifting as the slope declines from -2.6480 to -3.7160 .

4.2 Artificially corroded steel bar

The condition-specific data collected from the tested steel bars in Ref. [11] are provided in Fig. 2, and are obtained from the corroded steel bar under artificial accelerated corrosion with impressed current (electrical). The tested steel bars in Ref. [21, 29] are obtained from corroded steel bar subjected to chloride salt spray, as represented in Table 2. The tested steel bars in Ref. [25] are obtained from the corroded steel bar under accelerated corrosion with impressed current (electrical) and cyclic wetting and drying conditions, which

are different from the condition-specific data. Moreover, There are only 4 data points in which $S(x^{(i)})$ is greater than 1 that are sifted from Ref. [25], with a total of 31 records, and no data points are sifted from Ref. [21, 29], as plotted in Fig. 2, indicating that these records are less similar to condition-specific data.

Similar to above, Fig. 2a shows the result of the dimensionless yield strength versus mass loss for the artificial corrosion steel bar database and the corresponding condition-specific data, and the dimensionless yield strength decreases slightly with mass loss level. The linear regression model after and before sifting results in the following equations:

$$X_{1,a}^a = -1.0060\xi_s + 1.0483 \quad R_a^2 = 0.6031 \quad (9a)$$

$$X_{1,b}^a = -0.9310\xi_s + 1.0885 \quad R_b^2 = 0.4732 \quad (9b)$$

where X_1^a is the dimensionless yield strength of the artificial corrosion steel bar. Although the linear regression equation derived in the condition-specific data and the records after sifting only shows a slight difference in the slope and intercept, the coefficient of determination increases obviously from 0.4732 to 0.6031, and the MSE decreases by 37.43% from 0.01029 to 0.00644.

Figure 2b shows that the dimensionless ultimate strength also decreases slightly with an increase in the mass loss level. The linear regression model after and before sifting are described by the following equations:

$$X_{2,a}^a = -0.9500\xi_s + 1.1010 \quad R_a^2 = 0.6022 \quad (10a)$$

$$X_{2,b}^a = -0.9180\xi_s + 1.1430 \quad R_b^2 = 0.4624 \quad (10b)$$

where X_2^a is the dimensionless ultimate strength of the artificial corrosion steel bar. The results of the linear regression equation are similar to that of Eqs. (9) showing a slight change of slope and intercept, while the coefficient of determination increases obviously.

The result of the dimensionless ratio of ultimate strength to yield strength versus mass loss for the artificial corrosion steel bar database and the corresponding condition-specific data is provided in Fig. 2c. The slope is still very close to 0 and further illustrates that linear model does not explain any of the corrosion variation in the dimensionless ratio of ultimate strength to yield strength around its mean for artificially and naturally corroded steel bar, with or without sifting.

Figure 2d shows the result of the dimensionless elongation versus mass loss. It should be pointed out that there is no collected information regarding the dimensionless elongation in Ref. [25]. The linear regression analysis results in the following equations:

$$X_{4,a}^a = -1.6650\xi_s + 1.1542 \quad R_a^2 = 0.4655 \quad (11a)$$

$$X_{4,b}^a = -1.4550\xi_s + 1.2070 \quad R_b^2 = 0.2089 \quad (11b)$$

where X_4^a is the dimensionless elongation of the artificial corrosion steel bar. The result shows that dimensionless elongation decreases considerably with an increase in the mass loss level of steel bar. The slope of the linear regression equation after sifting also shows a more serious declining trend with mass loss level than that before sifting, as seen in the slope decline from -1.4550 to -1.6650 . The value of the slopes regarding dimensionless elongation are smaller than the dimensionless yield strength and the dimensionless ultimate strength, indicating that ductility decreases much faster than the strength of the corroded steel bar.

5 Discussion

According to natural and artificial accelerated corrosion conditions of the steel bars, the 2 cases are discussed individually in the following.

For natural corrosion reinforcement, the mechanical behavior decrease with the mass loss of steel bar, the slope of the linear regression equations after sifting decrease considerably with corrosion level compared to those before sifting, and the intercept with Y axis has a tendency to increase after sifting. This finding may suggest that the effect of corrosion on the mechanical properties of steel bars is underestimated when the effects of site conditions are not considered and all the sample points are taken into consideration.

In addition, the sifted records appear to cluster around the condition-specific data, indicating that their characteristics for dimensionless mechanical behavior versus mass loss of steel bar are indeed similar. In this work, 41 sifted records from the natural corrosion steel bars database with 210 records are used, along with 34 out of 144 records from the atmospheric zone, and 7 out of 66 records from the marine environment. Most of the sifted records are from the corroded steel bars in the atmospheric zone, while the corroded steel bars in the marine environment are basically eliminated, indicating that these records are highly similar to condition-specific data because most of them have the same environmental conditions. It should also be noted that not all corroded steel bars from marine environments have small $S(x^{(i)})$, and three are even larger, as seen in Table 7. This may be attributed to the large variation of corrosion on the mechanical properties of steel bars in marine environments, in which the mechanical

properties of a few corroded steel bars may be similar to those of atmosphere areas in the process of data mining.

For artificially corroded steel bars, as shown in Fig. 2, the dimensionless yield strength, dimensionless ultimate strength, and dimensionless elongation decrease with the mass loss of steel bar. The sifted records also appear to cluster around the condition-specific data, indicating that their trends for dimensionless mechanical behavior versus mass loss of corroded steel bar are indeed similar. There are 162 sifted records from the artificial corrosion steel bars database with a total 436 records, 158 out of 390 records subjected to artificial corrosion by impressed current (electrical), 4 out of 31 records obtained by artificial corrosion under impressed current and cyclic wetting and drying conditions, and 0 out of 15 records with chloride salt spray. The sifted records are mostly from the corroded steel bars subjected to impressed current, and the corroded steel bars subjected to other conditions are basically eliminated, indicating that these records are highly similar to condition-specific data because most of them have the same corrosion conditions. It should be noted that the slope of these linear regression equations, derived from the condition-specific data and the records after sifting, considerably larger than those before sifting. This result suggests that if the effects of site conditions are not considered and all sample points are taken into consideration, the effect of corrosion on the mechanical properties of steel bars might be underestimated. In addition, the corresponding R^2 experiences a significant increase, while the MSE has a significant decrease after the sifting process.

6 Conclusion

Corrosion effects on mechanical property deterioration of steel bar might be different for different corrosion environments as the literatures review showed a large coefficient of variation for the data collected. In this study, a similarity measure method was proposed to sift corroded steel bars exposed to different corrosion environments which share similar mechanical properties. The assumption of the proposed method is that the condition-specific tensile behaviors of the corroded steel bars obey multivariate normal distribution.

In this study, both naturally and artificially accelerated corroded steel bar databases were sifted for records similar to a set of corresponding condition-specific corrosion steel bar datasets based on a similarity measure method. The sifted similar records were combined with the limited condition-specific data to carry out a linear regression analysis, and the following conclusions can be drawn:

In the naturally or artificially corroded steel bar database, the similarity measure method is effective in the

sense that the sifted records in the database appear to cluster around the condition-specific data. This finding indicates that their characteristics for dimensionless mechanical behavior versus mass loss of corroded steel bar are indeed similar. Moreover, almost all the sifted records share the same corrosion conditions to those of condition-specific data.

Based on the similarity measure method, for both types of corroded steel bars, the sifted records identified as “similarity” can be used for linear regression analysis. When combined with the limited condition-specific data, the coefficient of determination increases obviously from 0.3750 to 0.6146 while the MSE decreases by 32.61% for dimensionless yield strength of naturally corroded steel, and larger coefficient of determination and smaller MSE can be obtained due to more similar corrosion steel bar characteristics relevant to the condition-specific data.

The slope of the linear regression equations derived from the condition-specific data and the records after sifting decrease significantly with corrosion level, compared to those before sifting. This result indicates that if the effects of site conditions are not considered and all sample points are taken into consideration, the effect of corrosion on the mechanical properties of steel bars may be underestimated.

The reported models for the relationship between mechanical properties and corrosion degree are only based on limited condition-specific data, and the statistical analysis model considering condition-specific obtained by similarity measure method has better prediction for the mechanical behavior of corroded steel bars due to a larger coefficient of determination.

There is an interesting difference between natural corrosion and artificial corrosion, by which the mechanical behavior with regard to naturally corroded steel bar decreases much faster than those considering artificially corroded steel bar. This finding indicates that the artificially corroded steel bar tests underestimate the effect of corrosion on the mechanical properties of steel bars.

This study was limited by the amount of data on mechanical property deterioration of naturally corroded steel bars. To obtain a better verification effect, a large amount of data is required. An issue that in the present work, similarity analysis was performed from four dimensionality and further study might incorporate more dimensionality, such as exposure situations and minimum cross-section area of corroded steel bars.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest to this work.

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