Research Article

Evaluation of the Methods for Estimating the Fully Reversed Unnotched Fatigue Limits of Steels

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Experimental determination of the fatigue limit is expensive considering the time and effort involved. To overcome this drawback, several empirical relations based on monotonic tensile properties and/or hardness have been developed for estimating the fatigue limit. In this study, ten estimation methods are evaluated and compared using the experimental data of 171 steels from literature. The scatter band criterion, standard deviation criterion, and statistical analysis are all used to evaluate and compare the predictability of the considered empirical relations. It is found that the fatigue limit can be well correlated with the Brinell hardness. In the absence of Brinell hardness, the ultimate tensile strength-based direct estimation method may be an alternative to estimate the fatigue limit of steels. It is not recommended to estimate the fatigue limit by using the indirect method on the basis of Basquin's fatigue properties estimated by the monotonic tensile properties even though the fatigue limit of steel is often determined by the experimental Basquin's curve at 10^6 cycles.

1. Introduction

Fatigue failures occur due to the application of fluctuating stresses that are much lower than the stress required to cause failure during a single application of stress. It has been estimated that fatigue contributes to approximately 90% of all service failures due to mechanical causes [1]. Fatigue is a problem that can affect any part or component subjected to cyclic loading. Automobiles on roads, aircraft wings and fuselages, ships at sea, nuclear reactors, jet engines, and land-based turbines are all subject to fatigue failures. However, fatigue phenomena are poorly understood until recently since they occur unexpectedly at relatively low stress levels [2]. As the century progressed and the use of metals expanded with the increasing use of machines, more and more failures of components subjected to repeated loads are recorded. Today, structural fatigue has assumed an even greater importance as a result of the ever-increasing use of high-strength materials and the desire for higher performance from these materials.

The fatigue limit has historically been a prime consideration in long-life fatigue design. For a given material, the fatigue limit has an enormous range, depending on surface finish, specimen or component size, type of loading, temperature, corrosive and other aggressive environments, mean stresses, residual stresses, and stress concentrations [1]. Most long-life S-N fatigue data available in the literature consist of fully reversed uniaxial fatigue strengths or fatigue limits of small, highly polished, unnotched specimens based on 10^6 to 5×10^8 cycles to failure in laboratory air environment. Therefore, determination of the fatigue limit from tests will be not only time-consuming but also expensive. In contrast, mechanics properties determined from monotonic tensile tests or hardness tests are more convenient than the fatigue tests. Over the years, many researchers have attempted to develop correlations among the monotonic tensile data or hardness and fatigue limit of materials [3–5]. Such correlations are desirable, considering the amount of time and effort required to obtain the fatigue limit, as compared to the monotonic tensile properties or hardness. If reliable correlations with reasonable accuracy can be

established, durability performance predictions and/or optimization analyses can be performed, while substantially reducing time and cost associated with material fatigue testing.

In the present study, ten methods utilized for estimating the fully reversed unnotched fatigue limits of steels from monotonic tensile properties or Brinell hardness are analyzed. The study is based on 171 steels which cover quite a range in variables that might affect fatigue behavior such as cyclic hardening/softening characteristics, tensile strengths covering the range from 331 to 2585 MPa, and Brinell hardness from 80 to 660.

2. The Estimation Methods

2.1. The Direct Methods. A common procedure to partially compare materials for their fatigue resistance is to plot the unnotched, fully reversed fatigue limit, σ_L , obtained under similar ideal laboratory conditions described above, versus the ultimate tensile strength, σ_u . A traditional idea is that the fatigue limit can be increased by raising the strength of a material, either by the chemical composition of the alloy, or by a heat treatment which increases the hardness. An approximation between the fatigue limit and ultimate tensile strength that is often used for steel is given as follows [1]:

$$\sigma_L = 0.5\sigma_u. \quad (1)$$

A plot of the fatigue limit vs. ultimate tensile strength is provided in Figure 1. The tested data shown in this figure are taken from AISI Bar Steel Fatigue Database [6] (Table 1), American Society for Metals (ASM) Reference Handbook [7] (Table 2), and SAE J1099 Technical Report [8] (Table 3). It can be seen that there is a good deal of scatter in the data and that predictions based on equation (1) have poor agreement with the data and are nonconservative for most of steels.

To improve the predictions, a modified correlation is given by Roessle and Fatemi [4]:

$$\sigma_L = 0.38\sigma_u. \quad (2)$$

Evaluation of equation (2) by using the tested data is also shown in Figure 1. Relatively good predictions can be obtained.

It should be mentioned that traditionally most fatigue limit data are obtained from rotating bending fatigue tests, where here the values are from axial fatigue tests. In axial fatigue tests, lower strengths are often obtained due to reasons such as higher probability of defects associated with larger stressed volume and bending resulting from specimen misalignment. Therefore, the smaller coefficient obtained by Roessle and Fatemi [4] can correlate the tested data better. In the present paper, equation (2) is referred to as the σ_u -based direct method.

The fatigue limit can also be estimated from the Brinell hardness, HB. An approximation has been suggested to be used [3], which is given as

FIGURE 1: Fatigue limit vs. ultimate tensile strength.

$$\sigma_L = 1.72HB. \quad (3)$$

A plot of the fatigue limit vs. Brinell hardness is provided by using the aforementioned experimental data (Figure 2). Similar to equation (1), there is a poor agreement between the data and the predictions obtained from equation (3). A modification provided by Roessle and Fatemi [4] is given as

$$\sigma_L = 1.43HB. \quad (4)$$

Evaluations show that equation (4) can provide better predictions (Figure 2). Equation (4) is hereafter referred to as the HB-based direct method.

2.2. The Indirect Methods. In view of the asymptotic character of the S-N curve, the fatigue limit can be defined as the constant stress amplitude at which the fatigue life becomes infinite or fatigue failures do not occur. However, in some cases where fatigue testing must be terminated at a specific large number of cycles, this nonfailure stress amplitude is often referred to as the endurance limit. Even the endurance limit needs not be a fatigue limit, but from the engineering point of view, the term of a fatigue limit is commonly used to refer to either case. Here, the fully unnotched fatigue limit σ_L at 10^6 cycles for steels is estimated from the monotonic tensile properties.

Many equations have been proposed to describe the S-N curve. The simplest one is Basquin's equation, which successfully describes the fatigue performance of steels for the high cycle regime [1]:

$$\sigma_a = \sigma'_f (2N_f)^b, \quad (5)$$

where σ_a is the fatigue stress amplitude, σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent, and $2N_f$ is the number of reversals to failure.

TABLE 1: Monotonic deformation properties and fatigue limit of the selected steels from the AISI Bar Steel Fatigue Database [6].

Materials	E (GPa)	σ_y (MPa)	σ_u (MPa)	σ_f (MPa)	RA (%)	ϵ_f	HB	σ_L (MPa)
1541	197	471.2	783.2	1207	55.1	0.8	180	260.0
1541	196	461	905.5	1247	41.7	0.54	195	311.7
1050M	211	449.6	821	1128	49.6	0.7	238	254.5
1050M	202	460	828.5	1065	34.1	0.416	220	360.2
1050M	220	2100	2360	2115	14.7	0.16	536	796.1
1090	219	728.8	1090	966	14	0.15	259	307.1
1090M	217	1065	1388	1427	25	0.29	357	404.1
1090	213	677.6	1147	1151	21.7	0.245	309	346.8
1090M	212	751.3	1252.3	1169	13.6	0.146	279	338.3
1090M	214	759.5	1124	840	37.6	0.47	272	376.0
1141AL	216	457.4	770.6	1207	57	0.85	223	286.0
1141AL	227	814.2	924.8	1405	59	0.88	277	432.0
1141Nb	220	417.8	695.2	1000	53	0.76	199	276.6
1141Nb	217	602.1	801.8	1228	54	0.77	241	341.8
1141V	214	449.9	725.2	1087	49	0.68	217	287.0
1141V	215	609.7	796.8	1243	58	0.88	252	332.2
1141V	220	493.5	789.4	1117	47	0.64	229	295.8
1038	201	330.7	582.2	898	54	0.77	163	222.6
1038	219	359.4	651.6	1051	53	0.76	185	240.8
1038	218	559.8	743	1292	69	1.16	245	317.6
10V45	213	465.2	764.6	1131	48	0.7	212	270.4
10V45	216	605.6	908.6	1197	42	0.5	269	374.3
1020	207	294.9	502.2	849	63.5	1.01	135	194.3
10B21	212	1062.3	1104.8	1573	70.5	1.22	322	536.9
1022	200	457.3	604.1	1587	68.7	1.16	195	230.6
1045	209	509.6	746.6	1151	62	1	222	278.5
1151V	206	452.3	760.8	1319	50.6	0.7	205	266.9
15V24	209	645.7	877.6	1363	61.1	0.9	243	379.2
4130AL	213	1284.5	1482.8	2055	44.3	0.6	442	527.6
4140	207	928.9	1042.9	1519	61.3	1	325	437.4
5140	218	956.7	1039.2	1445	52.7	0.8	305	496.8
5150	210	471.8	867.1	1382	55.8	0.8	245	294.5
51B60	200	1830	1970	1968	21.6	0.23	450	771
9254V	206	1870	2050	2118	35.1	0.4	536	710.2
1070	207	520	659	1360	36.2	0.5	280	339.3
C-70	201	765	964	837	16.8	0.197	241	340.2
15B35	219	866.4	939.9	1747	64.5	1.04	286	467.8
4620	208	687.5	997.8	1530	58.2	0.872	289	368.5
4320	202	920	994	1336	63	0.99	188	547.1
4620	211	892	964	1651.9	61.9	0.966	289	453.5
5120	214	780	1008	1287	58	0.87	252	471.8
9310	197	804	902	1418	70.8	1.23	260	464.1
8822	204	918	1131	1362	56	0.88	252	442.1
8620	203	1357	1764	801.4	13.9	0.15	457	805.7
4320	201	1344.5	1705.3	2197.8	55.5	0.811	445	774.5
4140	197	1297	1390	1521.5	48.3	0.66	377	602.5
4140	200	1305	1400.5	1771	48.2	0.657	380	607.5
4140	204	1330	1537	1705.2	42.1	0.546	410	626.3
4140	205	1314	1445.8	1754.5	52.1	0.736	390	697.3
4140	199	1255.1	1355.1	1332.7	38.8	0.492	370	679
4140	201	1341	1474.2	1786.2	52.5	0.745	396	730.4
8620	207	1401.7	1677.2	1851.7	14.2	0.153	439	731.1
41B17M	213	826.9	872.3	1304	68	1.137	277	465.5
86B20	205	989	1034.1	869	63.7	1.013	294	498.6
4140	213	1669.2	1924.3	1859	15.7	0.163	477	587.7
41B17M	216	863.1	904	1245.4	64.7	1.04	277	480.5
4140	206	1290.7	1380.4	1384.5	23.6	0.269	394	554.81
86B20	206	1198	1502	968.2	59.7	0.909	401	494.8
5160H	209	1604.2	1761.2	1843.8	30.2	0.359	456	736.9
9254	206	1841	2020	3644	51	0.71	508	664.6

TABLE 1: Continued.

Materials	E (GPa)	σ_y (MPa)	σ_u (MPa)	σ_f (MPa)	RA (%)	ϵ_f	HB	σ_L (MPa)
15V41	193	665.5	1070.7	766.5	32.6	0.395	303	431.9
4140	201	1363	1514	2071	48	0.65	405	552.4
1552	196	420	964	1526	45	0.59	276	387.2
8620	208	1566	1785	2206.4	39	0.49	461	614.6
4140	203	1157.5	1247.3	1311.3	47.5	0.646	409	601.9
4140	207	1167.1	1239.5	1537	47.2	0.64	417	575.2
4140	206	1622.2	1818.3	2016.7	42.6	0.555	477	637.83
4140	208	1261	1332.7	1517.6	44	0.581	375	574.2
8822	212	883.5	945.7	1170.2	67.2	1.115	297	511.2
8822	210	990	1334.7	1542.3	46.9	0.633	301	549.3
8822	194	1135	1215	2690	59.4	0.903	338	608.5
8822	208	1528	1723	3387	50	0.672	449	535.3
8620	212	693.5	991	1411.1	54	0.776	326	380.4
8620	210	795.8	1145.2	1585.7	50.8	0.711	352	430.2
8620	214	989.5	1310.8	1711.2	52	0.736	382	528.2
4320	194	620.5	905	1966	59.2	0.896	261	391.8
4320	194	745	1010	1984	57	0.846	288	466.3
4320	194	867	1238	2336	55.2	0.804	343	676.6
9310	196	666	883	1596	61.4	0.899	255	450
9310	196	850	1085	2155	57.5	0.857	306	531.5
9310	195	990	1201	2172	56.5	0.832	334	533.2
20MnCr5	194	852	1053	1991	56.5	0.832	299	489
20MnCr5	194	1071	1337	2351	52	0.74	366	606.8
1538MV	193	650.3	973.4	1038.7	28.3	0.333	285	439.1
1538MV	194	628	943	1069.8	36.4	0.452	277	382.3

TABLE 2: Monotonic deformation properties and fatigue limit of the selected steels from the ASM Handbook [7].

Materials	E (GPa)	σ_u (MPa)	σ_f (MPa)	RA (%)	ϵ_f	HB	σ_L (MPa)
A538A	185	1515	1896	67	1.1	405	644.5
A538B	185	1860	2137	56	0.82	460	762.1
A538C	180	2000	2241	55	0.81	480	811.3
AM-350	180	1905	2179	20	0.23	496	612.4
H-11	205	2585	3172	33	0.4	660	1037.2
RQC-100	205	940	1069	43	0.56	290	449.1
RQC-100	205	930	1331	67	1.02	290	449.1
10B62	195	1640	1779	38	0.89	430	673.4
1005-1009	205	360	717	73	1.3	90	157.2
1005-1009	205	470	745	66	1.09	125	218.8
1005-1009	200	415	641	64	1.02	125	187.2
1005-1009	200	345	848	80	1.6	90	111.1
1015	205	415	724	68	1.14	80	167.2
1020	205	440	710	62	0.96	108	156.9
1040	200	620	1048	60	0.93	225	202.0
1045	200	725	1227	65	1.04	225	308.7
1045	200	1450	1862	51	0.72	410	645.0
1045	205	1345	1862	59	0.89	390	541.7
1045	205	1585	2103	55	0.81	450	650.1
1045	205	1825	2275	51	0.71	500	712.7
1045	205	2240	2723	41	0.52	595	841.4
1144	195	930	1158	33	0.51	265	313.3
1144	200	1035	1517	25	0.29	305	429.5
1541F	205	950	1276	49	0.68	290	423.3
1541F	205	890	1276	60	0.93	260	455.1
4130	220	895	1420	67	1.12	258	382.4
4130	200	1425	1820	55	0.79	365	523.3
4140	200	1075	1524	60	0.69	310	571.7
4142	200	1060	1117	29	0.35	310	339.8
4142	205	1415	1827	48	0.66	380	571.7

TABLE 2: Continued.

Materials	E (GPa)	σ_u (MPa)	σ_f (MPa)	RA (%)	ε_f	HB	σ_L (MPa)
4142	200	1550	1896	47	0.63	400	513.5
4142	200	1760	1999	42	0.54	450	626.5
4142	200	2035	2068	20	0.22	475	629.9
4142	200	1930	2103	37	0.46	450	570.4
4142	205	1930	2172	35	0.43	475	670.0
4142	205	2240	2654	27	0.31	560	729.9
4340	195	825	1089	43	0.57	243	302.4
4340	200	1470	1558	38	0.48	409	534.1
4340	195	1240	1655	57	0.64	350	549.4
5150	195	1670	1931	42	0.87	430	688.9
52100	205	2015	2193	11	0.12	518	700.4
9262	205	925	1041	14	0.16	260	371.2
9262	195	1000	1220	33	0.41	280	423.0
9262	200	1565	1855	32	0.38	410	811.3
950C	205	565	931	64	1.03	159	205.1
950C	205	565	1000	69	1.19	150	196.6
950X	205	440	752	65	1.06	150	210.5
950X	205	530	1000	72	1.24	156	235.5
980X	195	695	1220	68	1.15	225	330.5

TABLE 3: Monotonic deformation properties and fatigue limit of the selected steels from SAE J1099 [8].

Materials	E (GPa)	σ_y (MPa)	σ_u (MPa)	σ_f (MPa)	RA (%)	ε_f	HB	σ_L (MPa)
1008	207	234	331	587.5	77.5	1.49	86	92.7
1008	203	255	365	649.3	77.9	1.51	90	100.3
1010	203	200	331	597.1	80.4	1.63	83	116.9
1015	207	228	414	695.5	68	1.14	80	146.3
1020	203	262	441	713.5	61.8	0.96	109	143.9
1020	186	255	393	644.5	64	1.02	108	129.5
1025	207	306	547	889.4	62.6	0.98	158	197.8
1045	207	517	752	1082.9	44	0.58	225	291.1
1045	207	1689	1827	2758.8	51	0.71	500	690.3
1045	207	1862	2241	3159.8	41	0.53	595	728.5
1045	207	424	718	1062.6	48	0.65	192	227.9
1045	207	1729	1956	2705.1	38.3	0.48	500	756.9
1045	207	1275	1344	2137.0	59	0.89	390	512.6
10B21	197	999	1048	1756.4	67.6	1.13	318	482.7
10B21	203	806	834	NA	NA	NA	255	369.6
10B22	203	806	834	NA	NA	NA	255	450.7
15B27	203	772	847	1431.4	69	1.17	250	410.2
15B27	203	854	916	1525.1	66.5	1.09	264	451.2
4130	200	1358	1427	2207.6	54.7	0.79	366	549.4
4130	221	778	896	1499.0	67.3	1.12	259	412.6
4140	207	848	938	NA	NA	NA	293	473.1
4140	200	1895	2033	2439.6	20	0.22	475	663.5
4142	200	1447	1551	2280.0	47	0.63	400	528.2
4142	200	1860	1929	2642.7	37	0.46	450	597.0
4142	207	1378	1413	2091.2	48	0.65	380	547.9
4142	207	1584	1757	2494.9	42	0.54	450	643.1
4142	207	1722	1929	2604.2	35	0.43	475	667.2
4340	200	1371	1468	2027.3	38.1	0.48	409	540.3
4340	190	834	1048	NA	NA	NA	275	429.8
4340	193	634	827	1185.9	43.4	0.57	243	301.9
4340	207	1102	1171	1826.8	56	0.82	327	502.2
5160	203	1488	1584	2212.8	39.7	0.51	430	634.2
0030	207	303	496	724.2	46	0.62	137	196.5
0050A	209	415	787	936.5	19	0.21	192	211.9
0050A	209	402	583	734.6	26	0.30	174	200.7
0050A	211	542	702	NA	NA	NA	206	258.0
8630	207	985	1144	1475.8	29	0.34	305	334.6

FIGURE 2: Fatigue limit vs. Brinell hardness.

If Basquin's equation is used to model the S-N curve, the fatigue limit can be determined by the following equation at 10^6 cycles:

$$\sigma_L = \sigma'_f (2 \times 10^6)^b. \quad (6)$$

In the absence of tested data, the fatigue strength coefficient, σ'_f , and the fatigue strength exponent, b , can be estimated using the monotonic tensile properties or Brinell hardness [4,9–12]. Then, the fatigue limit, σ_L , can also be estimated indirectly by substituting the predicted σ'_f and b into equation (6). This method will be hereafter referred to as indirect method.

Based on the indirect method, the fatigue strength coefficient and the fatigue strength exponent can be predicted by six existing estimation methods [4,9–12] firstly, and then the fatigue limit is calculated using equation (6). The six existing estimation methods considered in this paper are listed in Table 4. In this table, E is the modulus of elasticity, σ_u is the ultimate tensile strength, HB is the Brinell hardness, σ_f is the true fracture strength, and ϵ_f is the true fracture ductility.

3. Evaluation of the Estimation Methods

As analyzed above, the direct methods proposed by Roessle and Fatemi [4] give better predictions than the methods shown in References [1, 3]. Therefore, the direct methods proposed by Roessle and Fatemi [4] are evaluated by using the tested data of 171 steels. The predicted fatigue limit, σ_{Pre} , is compared with the experimental one, σ_{Exp} , in Figure 3. For comparison purpose, the same tested data are also used to evaluate the aforementioned six indirect methods (Figure 4). In these figures, the dotted lines, solid lines, and dashed-dotted lines represent factors of $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ scatter band, respectively. It can be seen that, for most of considered steels, the MFPCM-based indirect method tends

to overestimate the fatigue limit, while the FPCM-based and USM-based indirect methods as well as the σ_u -based direct method tend to underestimate the fatigue limit. Both MUSM-based and HM-based indirect methods tend to overestimate the fatigue limit when the experimental fatigue limit is low (about the experimental fatigue limit less than 400 MPa), while underestimations are presented when the experimental fatigue limit is high (about the experimental fatigue limit larger than 400 MPa). As for the HB-based direct method, it may be said to provide the best estimation results among all the eight estimation methods.

Most of the work done in comparing both the direct and indirect methods use the scatter band criterion where the percentage of predicted fatigue limit versus experimental data falling within a scatter band is compared (Table 5). Factors of $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ deviation from tested values are included in this table, along with the percentages of the data within each factor. It can be seen that the HB-based direct method has the most data with all deviation factors. For example, 86.5% of the predicted values are within a factor of $\pm 20\%$ of the experimental values based on the HB-based direct method. In contrast, the best results predicted by MM-based method among the considered indirect methods from the literature are 76.6% of the predicted fatigue limit within the same factor of experimental values.

It should be noted here that one of the shortcomings of the scatter band criterion is that the trend of the correlation between prediction and experiment cannot be captured. Comparison of the HB-based and σ_u -based direct methods with experimental data using scatter band criterion is schematically shown in Figure 5. It is observed that both the HB-based and σ_u -based direct methods predict well within the scatter band and hence have to be considered as equal. However, the trend of the HB-based direct method with experimental data is closer than that of the σ_u -based direct method, which is not captured by the scatter band criterion. To overcome this drawback, the standard deviation criterion is introduced to compare different estimation methods:

$$S_D = \sqrt{\frac{1}{n_p - 1} \sum_{i=1}^{n_p} [\ln(\sigma_{Pre}) - \ln(\sigma_{Exp})]^2}, \quad (7)$$

where n_p is the number of experimental data. It can be seen that the bigger the S_D is, the more scattered the predictions are. The comparisons using the standard deviation criterion are also tabulated in Table 5. It is shown that the HB-based direct method provides the best predictions.

In order to have a better quantitative comparison, the comparisons for different estimation methods are also given in the format of fitted probability density functions (PDF) for the predicted errors. For the statistical study, each data set is sorted in ascending order, and then each data point is associated with its mean rank. After that, each data set is fitted using the selected probability distribution. Here, the log-logistic distribution is selected based on the recommendation of Meggiolaro and Castro [12]. The cumulative distribution function of the log-logistic distribution function is given by the following equation [13]

TABLE 4: Approximation methods for Basquin's fatigue properties.

Approximation methods	σ'_f (MPa)	b
Four-point correlation method (FPCM) [9]	$1.12\sigma_u (\sigma_f/\sigma_u)^{0.893}$	$-0.0792 - 0.179\lg(\sigma_f/\sigma_u)$
Universal slopes method (USM) [9]	$1.9018\sigma_u$	-0.12
Modified universal slopes method (MUSM) [10]	$E \times 0.623 (\sigma_u/E)^{0.832}$	-0.09
Modified four-point correlation method (MFPCM) [11]	$\sigma_u (1 + \varepsilon_f)$	$\frac{1}{6} \{ \lg[0.16(\sigma_u/E)^{0.81}] - \lg(\sigma_f/E) \}$
Medians method (MM) [12]	$1.5\sigma_u$	-0.09
Hardness method (HM) [4]	$4.25HB + 225$	-0.09

FIGURE 3: Comparison of the direct methods using the tested data from [6–8]: (a) HB-based and (b) σ_u -based.

FIGURE 4: Continued.

FIGURE 4: Comparison of the indirect methods using the tested data from [6–8]: (a) FPCM-based method, (b) MFPCM-based method, (c) USM-based method, (d) MUSM-based method, (e) MM-based method, and (f) HM-based method.

TABLE 5: Comparison of estimation methods in terms of evaluation values.

	HB-based	σ_u -based	FPCM	MFPCM	USM	MUSM	MM	HM
$\pm 10\%$	0.544	0.450	0.440	0.102	0.327	0.392	0.427	0.392
$\pm 20\%$	0.865	0.772	0.687	0.361	0.608	0.754	0.766	0.766
$\pm 30\%$	0.977	0.965	0.892	0.512	0.877	0.889	0.918	0.895
S_D	0.155	0.170	0.199	0.353	0.240	0.182	0.167	0.187

$$F(x) = \frac{x^p}{a^p + x^p}, \quad x > 0, a > 0, p \geq 1, \quad (8)$$

where p is a shape parameter and a is a scale parameter. The corresponding probability density function (PDF) of the log-logistic distribution is given by [13]

$$f(x) = \frac{pa^p x^{p-1}}{(a^p + x^p)^2}, \quad x > 0, a > 0, p \geq 1. \quad (9)$$

The cumulative probability P_f of estimated data is evaluated by the mean rank method as

$$P_f = \frac{i}{I+1}, \quad (10)$$

where i is the rank number and I is the total number of considered steels. Symbols show the $\sigma_{pre}/\sigma_{exp}$ ratio of the considered eight estimation methods (Figure 6). Optimum values of the parameters a and p are obtained by applying

FIGURE 5: Schematic showing the limitation in comparing two different methods using scatter band criterion.

FIGURE 6: Continued.

FIGURE 6: The estimates of the considered estimation methods (the curvilinear lines show the fit of log-logistic distribution): (a) HB-based method, (b) σ_u -based method, (c) FPCM-based method, (d) MFPCM-based method, (e) USM-based method, (f) MUSM-based method, (g) MM-based method, and (h) HM-based method.

the least squares method [14]. The curvilinear lines indicate the results of fitting (Figure 6). The optimum values of a and p are also presented in Figure 6. Then, the best-fitted distributions of different estimation methods are shown in Figure 7. It is clearly shown that the FPCM-based and USM-based indirect methods as well as the σ_u -based direct method provide underestimations, while the MFPCM-based indirect method provides overestimation. The HB-based direct method provides reasonable predictions while somewhat underestimations are shown in Figure 7. In contrast to the considered estimation methods, the HB-based direct method on the basis of Brinell hardness provides the best predictions for the fatigue limits of most of steels.

Although the HB-based direct method presents the best predictions among the considered estimation methods, it is known that, for advanced steels, the predictability of the fatigue limit based on monotonic properties often fails. The failed predictions may lie in the high notch sensitivity since a lot of the advanced steels belong to the high-strength materials. The inclusions act as micronotches in the material which can generate fatigue crack nuclei, especially in high-strength material [15]. Because of the high-yield strength of these materials, they have a high notch sensitivity, even for micronotches [15]. Therefore, in high-strength steel, inclusions are more harmful because of the higher notch sensitivity. Then, the predictability of the fatigue limit based on monotonic properties for advanced steels is more challengeable, which is needed to be studied further.

4. Conclusions

- (1) The Brinell hardness, HB, can correlate the fatigue limit well. The fatigue limit can be estimated well by the HB-based direct method for most of considered steels. In the absence of HB, the σ_u -based direct method is recommended to calculate the fatigue limit.
- (2) In contrast to the direct methods, all the indirect methods are not only relatively complicated to use but also more scattered in predictions.

FIGURE 7: Probability density functions of the considered estimation methods.

Finally, it is important to point out that HB-based direct method is not physical law although it correlates the fatigue limit of many steels well. It is still an empirical equation. Therefore, such estimates should not be used to replace experiments. Whenever possible, the fatigue limit should be obtained from the tested data. These estimates, even the HB-based direct method, are only admissible during the first stage of design.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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