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Overall buckling behaviour and design of high-strength steel welded section columns

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ABSTRACT

Practical use of high-strength (HS) steel in contemporary construction has become one of the most important design solutions. Loading capacities of columns may benefit enormously from the HS steel, whilst their overall buckling behaves differently compared with conventional mild (CM) steel columns due to varying effects of initial imperfections and inelastic properties of the HS steel materials. Despite a number of investigations regarding the HS steel columns being undertaken, there is lack of research focused on variation of HS steel grades and their effects. To deepen understanding of overall buckling behaviour of the HS steel columns, a comprehensive review of an extensive body of column test data available in the literature is carried out in the present paper, based on which a three-dimensional finite element (FE) model developed herein is validated. Parametric analyses are subsequently undertaken with various HS steel grades, welded cross-sectional geometric parameters, slenderness values and initial imperfections being involved. The FE analysis results are also compared with calculation values in accordance with national standards. It has been demonstrated that with an increase of the grade of HS steel, effects of imperfections decrease whilst that of Y/T ratios are rather limited; reduction effects on the overall buckling strength become less severe, and therefore higher column curves available in current national standards may be selected and imperfection factors in the alternative column curve equations proposed herein descend accordingly. In addition, new theoretical column curves based on Perry-Robertson formula are developed by introducing imperfection parameters independent on the steel strength.

1. Introduction

High-strength (HS) structural steel has attracted increasing attention from both practical engineers [1–3] and academic researchers [4–6], and their usage in contemporary steel construction has become an important design solution. The most essential attribute of such advanced steel in terms of higher yield strength (no less than 460 MPa) compared with conventional mild (CM) steel is particularly beneficial to steel columns subjected to compression. Loading capacities of the columns may be significantly improved, whilst their overall buckling behaviour is quite distinct from CM steel columns. With an increase of the yield strength of HS steel, compressive residual stresses within cross-sections, of which ratio to the yield strength becomes markedly lower [7,8], possess much less severe effects on the overall buckling behaviour; whilst initial bending-induced stresses may also result in reduced effects [9] because of their descending ratios to the yield strength of steel. As a consequence, research and development of robust design methodologies on overall buckling behaviour of HS steel columns are of great significance for providing economical but safe design solutions.

Despite a number of experimental programmes of HS steel columns hitherto having been undertaken and reported in the literature, they focused generally on some individual steel grade without considerations of its variation in the analyses of buckling mechanism as well as in the development of design methods. The very first column tests on HS steel seem to be that by Usami and Fukumoto [10] in 1982, in which five welded box section columns excluding stub ones fabricate from HT80 (690 MPa) HS steel were tested. Rasmussen and Hancock [11] undertook 11 welded box and I-shaped column tests for BISALLOY 80 (690 MPa) HS steel in 1995. After 2010, the authors investigated experimentally and numerically the overall buckling behaviour of four S690 HS steel columns and four S960 ones with end restraint [12], as well as 12 Q460C HS steel welded section columns [13] and six Q960 ones [14]. Similarly, Wang et al. carried out 12 Q460 HS steel welded section column tests as well as corresponding finite element (FE) analyses [15,16], and Zhou et al. [17] designed six Q460 HS steel welded H-shaped section columns with their overall buckling behaviour being investigated experimentally ad numerically. More recently, Li et al. [18–19] tested 12 Q690 HS steel welded box and I-section columns, with FE parametric analyses being conducted. Chung et al. [20] experimentally investigated seven Q690

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Table 1
Detailed information of HS steel column test specimens available in literature.

Specimen	Cross-sectional geometry (mm)	L_0 (mm)	e (mm)	f_y (MPa)	$P_{u\cdot t}$ (kN)	λ_n	φ	$P_{u\cdot FEA}$ (kN)	$\frac{P_{u\cdot FEA}}{P_{u\cdot t}}$
S-35-22 [10]	B139.00 × 6.00	1880.0	1.18	741.0	2112.0	0.654	0.853	2147.3	1.017
S-50-22 [10]	B138.98 × 6.01	2690.0	0.85	741.0	1798.0	0.967	0.740	1658.1	0.922
R-50-22 [10]	B139.00 × 6.00	2090.0	0.83	741.0	1622.0	0.930	0.745	1506.3	0.929
R-65-22 [10]	B138.98 × 6.01	2720.0	0.66	741.0	1299.0	1.210	0.594	1327.8	1.022
ER-50-22 [10]	B138.98 × 6.01	2090.0	11.32	741.0	1220.0	0.932	0.558	1221.5	1.001
B1150C [11]	B98.90 × 5.00	1149.0	0.50	705.0	1174.0	0.562	0.911	1161.7	0.990
B1150E [11]	B97.50 × 4.95	1150.0	2.10	705.0	1137.0	0.570	0.904	1076.4	0.947
B1950C [11]	B98.22 × 4.96	1950.0	0.50	705.0	1078.0	0.960	0.849	962.8	0.893
B1950E [11]	B99.34 × 4.97	1950.0	3.20	705.0	926.0	0.948	0.719	864.8	0.934
B3450C [11]	B100.14 × 4.97	3451.0	0.40	705.0	469.0	1.664	0.361	478.6	1.020
B3450E [11]	B99.78 × 4.94	3451.0	2.90	705.0	438.0	1.670	0.340	442.2	1.010
I1000C [11]	H155.40 × 141.50 × 7.70 × 7.70	1000.0	0.70	660.0	2092.0	0.545	0.952	1965.0	0.939
I1000E [11]	H157.14 × 141.10 × 7.67 × 7.71	1000.0	1.30	660.0	2192.0	0.550	0.991	1923.1	0.877
I1650C [11]	H156.90 × 141.50 × 7.70 × 7.66	1649.0	0.40	660.0	1751.0	0.896	0.800	1739.5	0.993
I1650E [11]	H158.42 × 141.50 × 7.71 × 7.75	1649.0	1.00	660.0	1682.0	0.900	0.762	1683.7	1.001
I2950E [11]	H157.50 × 140.30 × 7.75 × 7.74	2950.0	2.00	660.0	745.0	1.627	0.337	795.3	1.067
S1-690-1300 [12]	I 120.5 × 100.2 × 10.0 × 8.3	1216.8	4.69	799.0	1857.9	0.477	0.821	2028.0	1.092
S2-960-1300 [12]	I 89.5 × 79.5 × 7.9 × 6.1	1103.7	8.73	962.5	1368.4	0.625	0.831	1268.6	0.927
S3-690-2700 [12]	I 121.1 × 100.0 × 10.0 × 8.0	2385.0	8.08	799.0	1656.5	0.927	0.739	1449.7	0.875
S4-960-2700 [12]	I 120.0 × 99.2 × 10.1 × 7.9	2384.9	11.85	996.0	2099.6	1.066	0.756	1487.2	0.708
S5-690-3600 [12]	I 79.8 × 70.4 × 6.0 × 6.1	2345.5	34.73	740.3	306.4	1.356	0.328	283.7	0.926
S6-960-3600 [12]	I 95.3 × 79.6 × 7.8 × 6.1	2673.3	15.32	962.5	434.6	1.424	0.260	564.9	1.300
S7-690-3600 [12]	I 59.7 × 49.9 × 5.1 × 5.2	2015.1	39.44	783.3	136.7	1.613	0.228	148.6	1.087
S8-960-3600 [12]	I 59.9 × 59.2 × 6.1 × 6.2	2086.8	17.97	1019.8	210.0	1.919	0.202	226.1	1.077
B1-460 [13]	B152.0 × 10.92	1080.2	5.24	531.9	3129.7	0.300	0.955	2944.5	0.941
B2-460 [13]	B141.1 × 14.83	1261.1	6.68	492.3	3642.3	0.374	0.988	3641.9	1.000
B3-460 [13]	B121.5 × 12.67	1549.4	1.44	492.9	2185.6	0.532	0.804	1961.7	0.898
B4-460 [13]	B102.4 × 11.04	1782.4	2.80	531.9	1503.8	0.760	0.701	1546.9	1.029
B5-460 [13]	B102.2 × 10.81	2279.8	11.89	531.9	930.6	0.972	0.443	899.1	0.966
I1-460 [13]	I 111.7 × 132.1 × 10.96 × 11.37	2571.4	3.13	531.9	1265.4	0.909	0.597	1296.8	1.025
H1-460 [13]	H209.4 × 210.0 × 14.80 × 15.02	1089.3	0.07	492.3	4487.2	0.332	1.014	4018.9	0.896
H2-460 [13]	H141.6 × 179.7 × 15.16 × 12.96	1312.1	2.11	492.3	2732.0	0.439	0.797	2822.0	1.033
H3-460 [13]	H150.2 × 151.5 × 11.08 × 11.35	1535.4	2.51	531.9	1998.6	0.677	0.770	1974.1	0.988
H4-460 [13]	H151.1 × 151.2 × 11.02 × 11.07	1815.1	3.90	531.9	1842.4	0.801	0.717	1828.0	0.992
H5-460 [13]	H111.2 × 131.9 × 10.76 × 11.34	2026.0	2.28	531.9	1398.8	1.001	0.669	1230.8	0.880
H6-460 [13]	H149.4 × 150.3 × 11.02 × 11.09	1315.2	3.06	531.9	2437.8	0.584	0.956	2122.9	0.871
B1-960 [14][a]	B142.6 × 13.99	1878.6	25.88	973.2	3779.5	0.775	0.540	3711.2	0.982
B2-960 [14]	B141.6 × 13.94	2879.8	3.13	973.2	4063.9	1.196	0.587	3704.1	0.911
B3-960 [14]	B141.5 × 13.92	4382.3	0.82	973.2	2193.4	1.822	0.317	1981.1	0.903
H1-960 [14][a]	H211.1 × 209.8 × 13.96 × 13.93	1882.5	18.67	973.2	4682.7	0.813	0.567	4300.3	0.918
H2-960 [14]	H209.5 × 210.8 × 13.93 × 13.93	2883.7	4.92	973.2	4282.2	1.238	0.519	4147.1	0.968
H3-960 [14]	H209.9 × 211.0 × 13.92 × 13.87	4381.5	4.83	973.2	2322.8	1.879	0.282	2157.9	0.929
H-3-80-1 [15]	H171.25 × 154.50 × 20.99 × 11.52	3320.0	2.08	540.9	1913.0	1.365	0.430	2034.2	1.063
H-3-80-2 [15]	H171.25 × 154.70 × 20.98 × 11.36	3304.0	1.70	540.9	2107.5	1.354	0.475	2093.4	0.993
H-5-55-1 [15]	H245.75 × 227.75 × 21.33 × 11.54	3320.0	0.33	464.0	4357.5	0.858	0.763	4288.0	0.984
H-5-55-2 [15]	H245.50 × 229.00 × 21.15 × 11.62	3320.0	3.13	502.5	4290.0	0.889	0.695	4345.7	1.013
H-7-40-1 [15]	H317.25 × 308.75 × 21.03 × 11.47	3320.0	3.00	540.9	7596.5	0.682	0.857	7581.7	0.998
H-7-40-2 [15]	H318.50 × 308.25 × 21.20 × 11.46	3320.0	1.58	540.9	7534.5	0.683	0.845	7771.5	1.031
B-8-80-1 [16]	B110.3 × 11.40	3320.0	3.00	505.8	1122.5	1.288	0.492	1141.6	1.017
B-8-80-2 [16]	B112.0 × 11.49	3260.0	0.60	505.8	1473.5	1.245	0.631	1403.2	0.952
B-12-55-1 [16]	B156.5 × 11.43	3260.0	4.90	505.8	2591.0	0.866	0.772	2375.1	0.917
B-12-55-2 [16]	B156.3 × 11.42	3260.0	3.80	505.8	2436.5	0.867	0.728	2418.6	0.993
B-18-38-1 [16]	B220.2 × 11.46	3260.0	2.40	505.8	3774.0	0.602	0.780	4146.6	1.099
B-18-38-2 [16]	B220.8 × 11.46	3260.0	3.40	505.8	4010.0	0.601	0.826	4120.5	1.028
L1-H10 [17]	H225.2 × 151.6 × 10.82 × 10.82	2120.0	2.12	550.2	1622.5	1.029	0.538	1640.9	1.011
L2-H10 [17]	H222.3 × 151.8 × 10.39 × 10.39	2719.0	2.72	550.2	1141.5	1.315	0.395	1211.2	1.061
L3-H10 [17]	H221.3 × 151.8 × 11.08 × 11.08	3318.0	3.32	550.2	839.5	1.600	0.274	981.1	1.169
L1-H10 [17]	H226.7 × 149.9 × 12.74 × 12.74	2120.0	2.12	515.7	2128.0	1.006	0.646	1814.6	0.853
L2-H10 [17]	H225.2 × 150.8 × 12.47 × 12.47	2720.0	2.72	515.7	1298.0	1.281	0.402	1363.7	1.051
L3-H10 [17]	H227.5 × 151.6 × 12.65 × 12.65	3321.0	3.32	515.7	1143.0	1.557	0.347	1059.8	0.927
B-30-1 [18]	B236.23 × 16.20	2811.0	27.80	624.0	5771.5	0.514	0.649	6447.5	1.117
B-30-2 [18]	B236.47 × 16.10	2812.0	4.90	772.0	9751.5	0.571	0.890	9643.7	0.989
B-50-1 [18]	B192.37 × 16.02	3610.0	0.90	772.0	6444.5	0.914	0.739	7299.6	1.133
B-50-2 [18]	B192.52 × 16.02	3612.0	2.30	772.0	7180.0	0.914	0.822	6934.0	0.966
B-70-1 [18]	B140.88 × 16.07	3610.0	0.10	772.0	3258.5	1.286	0.526	3707.3	1.138
B-70-2 [18]	B140.48 × 16.08	3609.0	1.50	772.0	2897.0	1.290	0.469	3444.8	1.189
H-30-1 [18]	H259.19 × 260.85 × 16.08 × 16.08	2011.0	2.00	772.0	8493.0	0.585	0.914	8486.9	0.999
H-30-2 [18]	H260.35 × 260.82 × 16.25 × 16.25	2010.0	0.50	772.0	8994.0	0.585	0.957	8891.5	0.989
H-50-1 [18]	H236.30 × 241.75 × 16.03 × 16.03	2912.0	0.50	772.0	7207.0	0.910	0.847	7663.6	1.063
H-50-2 [18]	H238.15 × 240.47 × 16.16 × 16.16	2911.0	1.00	772.0	7124.5	0.916	0.832	7456.5	1.047
H-70-1 [18]	H204.78 × 209.21 × 16.26 × 16.26	3511.0	2.80	772.0	3039.0	1.263	0.410	4021.3	1.323
H-70-2 [18]	H205.24 × 209.38 × 16.24 × 16.24	3512.0	1.50	772.0	3690.0	1.262	0.498	4248.5	1.151
B-120-45 [22][a]	B120.68 × 12.54	3392.0	45.52	563.0	861.9	1.261	0.282	898.4	1.042

(continued on next page)