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CYCLIC ROTATION CAPACITY OF BEAM-TO-COLUMN CONNECTIONS USING VARIOUS STEEL GRADES

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Abstract

In the 1995 Kobe earthquake, many steel structures suffered damage at beam-to-column connections. And in those damaged buildings, fractures of a beam flange at the beam-to-column connections were observed. After that, a remarkable number of studies have been conducted to prevent early fracture at beam-to-column connections and enhance the plastic deformation capacity of steel beams. In these researches, it was pointed out that the small joint efficiency of the beam web, which is caused by the out-of-plane deformation of the skin plate of RHS column used for moment resisting frames in Japan, decreases plastic rotation capacity of the beam limited by the fracture of the beam flange. In the high-rise buildings of Japan, the on-site full penetration welding to beam flanges has to be achieved with the bolted beam-web joint (WBFW type connection). However, the bolted beam-web joint has problem of the poor joint efficiency. Recently, the plastic deformation capacity of the WBFW connections subjected to a long-duration earthquake of ground motion with many cycle of small amplitude of deformation has become a very important issue for structural engineers in Japan. The plastic deformation capacity of the WBFW type connections is evaluated by low cycle fatigue characteristics plotted with fracture life as the vertical axis and ductility factor as the horizontal axis. However, it is difficult to evaluate several test results with various test conditions such as steel grade and beam span.

In this paper, cyclic loading tests focusing on suggesting an appropriate evaluation method of plastic deformation capacity of WBFW type connections were carried out. Three types of specimen were tested. Each group of specimens has similar joint efficiency and connection details. The 400MPa conventional strength steel was used for the first group of specimen, and the 490MPa conventional strength steel and the 590MPa high strength steel was used for the second and third ones, respectively.

The test results can be summarized as follows:(1) the beam-to-column connection made of the 590MPa high strength steel fractured in 14 cycles of constant rotation angle loading of the $1.5\theta_p$, although that of the 400MPa conventional strength steel showed sufficient plastic deformation capacity; (2) the plastic deformation capacity of the 590MPa high strength steel is almost the same as that of the others in evaluation of low cycle fatigue characteristics based on the maximum rotation angle; (3) finally, it was very effective to evaluate several test results with various test condition such as steel grade and beam span.

Keywords: beam-end connection; cyclic loading test; plastic rotation capacity; material strength; beam section size

1. Introduction

In the 1995 Kobe earthquake, many steel structures suffered damage at beam-to-column connections. In those damaged buildings, fractures of beam flange at the beam-to-column connections were observed. After that, a remarkable number of studies have been conducted to prevent early fracture at beam-to-column connections and enhance the plastic deformation capacity of steel beams. In these research studies, it was pointed out that the small joint efficiency of the beam web, which is caused by the out-of-plane deformation of the skin plate of the rectangular hollow section (RHS) column used for moment resisting frames in Japan, decreases the plastic rotation capacity of the beam limited by the fracture of the beam flange. In the high-rise buildings of Japan, the on-site full penetration welding to beam flanges has to be achieved with the bolted beam-web joint (WBFW type connection). However, the bolted beam-web joint has problems due to its poor joint efficiency. Recently, the plastic deformation capacity of the WBFW type connections subjected to a long-duration of ground motion with many small amplitude cycles has become a very important issue for structural engineers in Japan. The plastic deformation capacity of the WBFW type connections is evaluated using its low cycle fatigue characteristics represented by graph with fracture life as the vertical axis and ductility factor as the horizontal axis. However, it is difficult to evaluate several test results with various test conditions such as steel grade and beam span.

In this paper, cyclic loading tests focusing on suggesting an appropriate evaluation method of plastic deformation capacity of WBFW type connections were carried out. And then, application of the evaluation method was verified by comparing with previous tests.

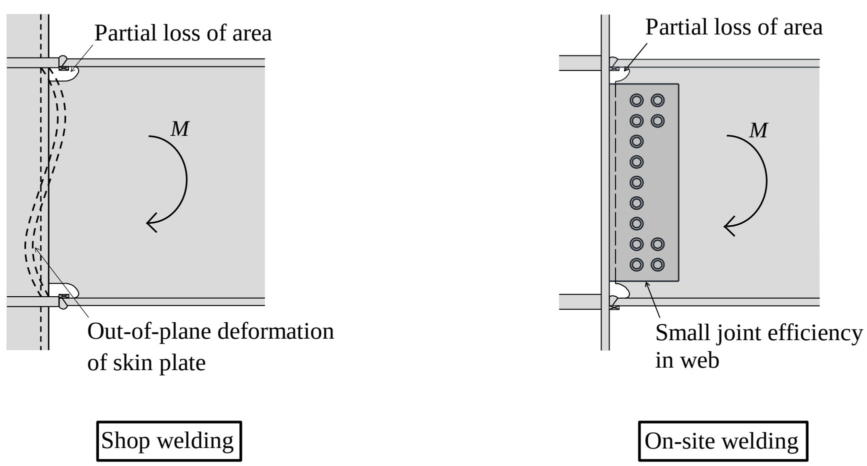


Fig. 1 – The difference of connection

2. Test plan

2.1 Test Specimen

The list of test specimens and the connection details are shown in Table 1 and Fig. 2, respectively. The specimen was a wide-flange beam made of section (depth x width) of H-600x200 with WBFW connection. The strong column was used as a jig. A difficult construction condition is realized by using the inside edge penetration at both beam flanges. The test specimens consist of three series that were made of a different strength of steel which were 400MPa conventional strength steel (400MPa steel), 490MPa conventional strength steel (490MPa steel), and 590MPa high strength steel (590MPa steel). The connection strength considered in designing the test specimen and the ratio of connection strength is summarized in Table 2. And, the adjustment results of the strength balance are shown in Fig.3. In order to adjust the strength balance between beam and beam-web joint, super high strength bolts (F14T) and high strength bolts (S10T) are used respectively for the beam-web joints made of different steel. The material test results and stress-strain relationship of the beam-flange are shown in Table 3 and Fig.4, respectively.

Table 1 – The list of test specimens

Steel grade	Column section	Beam section	Beam span L (mm)	Ductility factor θ_{max}/θ_p	web bolt
400MPa steel	BH500x400x32x19	RH600x200x11x17	3,000	1.51	13-M20 (S10T)
				2.02	
490MPa steel				1.33	
				1.53	
				2.04	
590MPa steel		BH600x200x12x19	3,000	1.11	13-M20 (F14T)
			3,050	1.15	
			3,000	1.19	
			3,050	1.39	
			3,050	1.84	

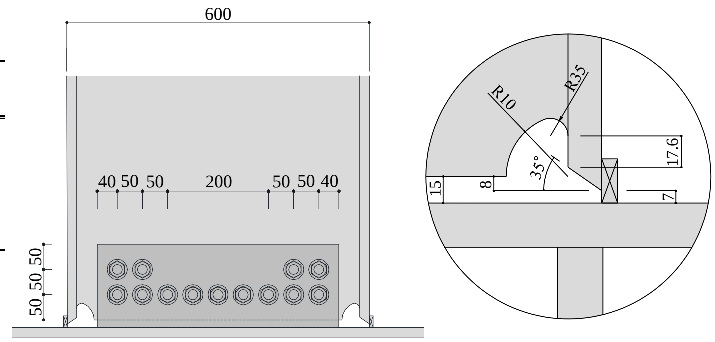


Fig. 2 – Connection detail

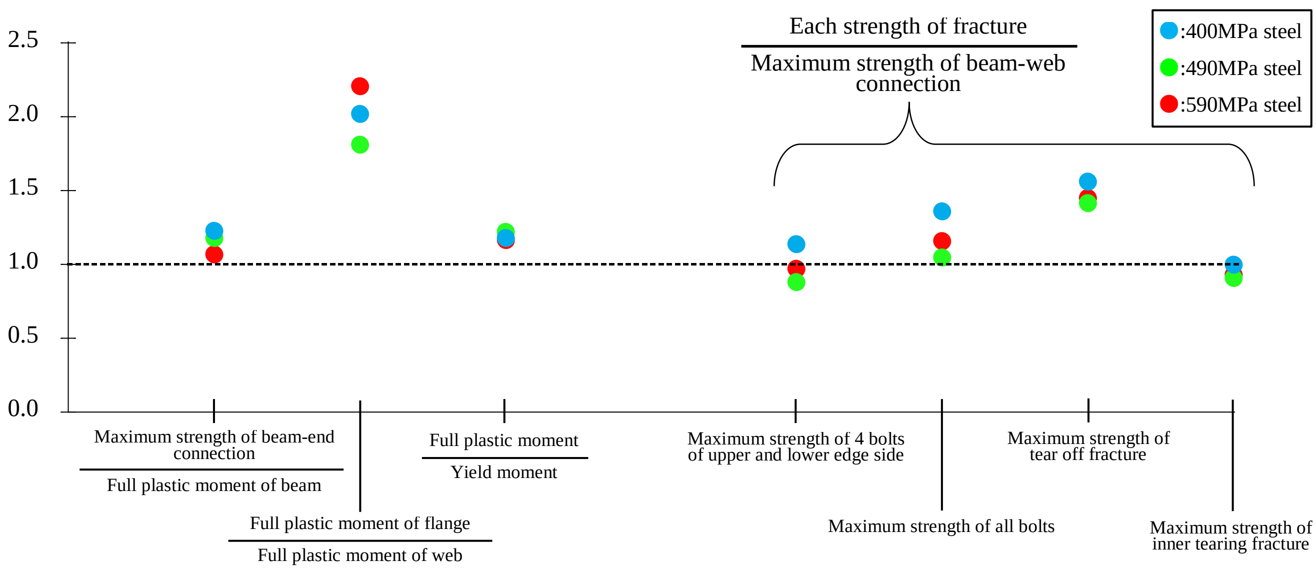


Fig. 3 – The adjustment results of strength balance

Table 2 – The connection strength considered in designing the test specimen and the ratio of connection strength

	Connection strength	590MPa steel			490MPa steel			400MPa steel		
		①	②	ratio (①/②)	①	②	ratio (①/②)	①	②	ratio (①/②)
1	Maximum strength of beam-end connection	$_jM_u$	$_bM_p$	1.07	$_jM_u$	$_bM_p$	1.18	$_jM_u$	$_bM_p$	1.23
		1797	1676		1308	1108		1130	915	
2	Full plastic moment of web and flange	$_bM_{fp}$	$_bM_{wp}$	2.21	$_bM_{fp}$	$_bM_{wp}$	1.81	$_bM_{fp}$	$_bM_{wp}$	2.01
		1154	522		713	394		612	304	
3	Yield and full plastic momennt	$_bM_p$	$_bM_y$	1.17	$_bM_p$	$_bM_y$	1.22	$_bM_p$	$_bM_y$	1.18
		1676	1427		1108	907		915	778	
4	Maximum strength of 4 bolts of upper and lower edge side	$_BM_{u1}$	$_jM_{wu}$	0.97	$_BM_{u1}$	$_jM_{wu}$	0.87	$_BM_{u1}$	$_jM_{wu}$	1.57
		370	381		263	301		363	231	
5	Maximum strength of all bolts	$_BM_{u2}$	$_jM_{wu}$	1.16	$_BM_{u2}$	$_jM_{wu}$	1.04	$_BM_{u2}$	$_jM_{wu}$	1.37
		442	381		314	301		316	231	
6	Maximum strength of tear off fracture	$_BM_{u3}$	$_jM_{wu}$	1.45	$_BM_{u3}$	$_jM_{wu}$	1.42	$_BM_{u3}$	$_jM_{wu}$	1.56
		553	381		427	301		360	231	
7	Maximum strength of inner tearing fracture	$_BM_{u4}$	$_jM_{wu}$	0.93	$_BM_{u4}$	$_jM_{wu}$	0.91	$_BM_{u4}$	$_jM_{wu}$	1.00
		354	381		273	301		231	231	

$_jM_u$: Maximum strength of beam-end connection, $_jM_{wu}$: Maximum strength of beam-web connection, $_bM_p$: Full plastic moment of beam, $_bM_{fp}$, $_bM_{wp}$: Full plastic moment of flange and web, $_bM_y$: Yield moment, $_BM_{u1}$: Maximum strength of 4 bolts of upper and lower edge side, $_BM_{u2}$: Maximum strength of all bolts, $_BM_{u3}$: Maximum strength of tear off fracture, $_BM_{u4}$: Maximum strength of inner tearing fracture

2.2 Loading method

The test setup is illustrated in Fig. 5. A constant rotation angle of ductility factor θ_{max} / θ_p shown in Table 1 is employed as the loading protocol for the each specimen. Here, the plastic rotation angle θ_p (400MPa steel: 0.0062rad., 490MPa steel: 0.0075rad., 590MPa steel: 0.0108rad.) is obtained from the full plastic moment M_p divided by the elastic stiffness K. Here, note that M_p and K is theoretical value. However, yield strength σ_y in calculating M_p was used in the material test results (Table 3).

Table 3 – Material test results

Steel grade	Member	Thickness t (mm)	Yield strength σ_y (N/mm^2)	Tensile strength σ_u (N/mm^2)	Rupture elongation $E.I.$ (%)
400MPa steel	Beam-flange	17	298	453	17.0
	Beam-web	11	319	468	20.6
490MPa steel	Beam-flange	17	347	508	25.9
	Beam-web	11	408	554	27.2
590MPa steel	Beam-flange	19	510	641	28.0
	Beam-web	12	539	658	27.5

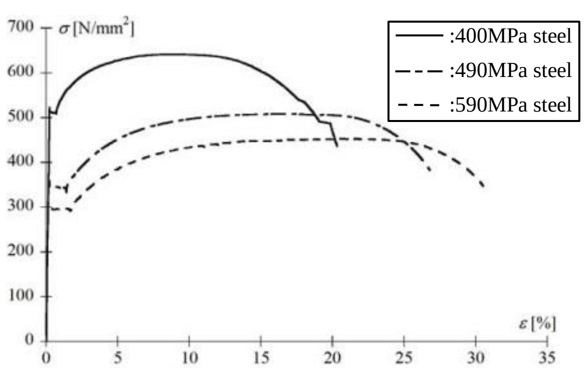


Fig. 4 – Stress-strain relationship

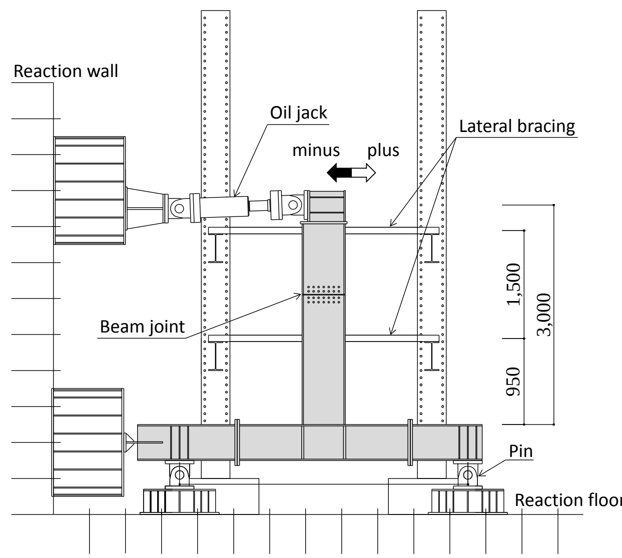


Fig. 5 – Setup

3. Test results and consideration

3.1 Overview of test results

The test results of each specimen are summarized in Table 4. In all of the specimens, the growth of a ductile crack at the toe of the weld access hole caused the rapid strength degradation. Compared to ductility factor of about 1.50 of each specimen, the number of loading cycles until fracture of 400MPa, 490MPa and 590MPa steel is 107, 64 and 14 cycles respectively. The test specimens of ductility factor of about 2.00 showed similar results to that of the ductility factor of about 1.50. Consequently, in the case of a comparison with the same ductility factor, the test results indicate that the plastic deformation capacity of high strength steel is lower than that of the conventional strength steel.

Overall behavior, M / M_p - θ / θ_p and M / M_p - θ relationship, are shown in Fig. 6 and Fig. 7. Compared to the same ductility factor, Fig. 6 indicates that the specimen made of high strength steel was fractured at an early stage. On the other hand, Fig. 7 indicates that the absolute rotation angle θ of the specimen made of high strength steel is larger. Consequently, large plastic rotation angle θ_p produces large deformation because the parameter of this paper is only material strength. It indicates that one of the reason why plastic deformation capacity is difference is the plastic rotation angle θ_p of each specimen. Here, the strain history of beam-end flange of each specimen is shown in Fig. 8. Strain history is used the mean value of strain gauge of beam-end flange occurred flexural tensile in the first cycle. In 1.0θ_p, the difference of strain by material strength is not observed. However, in case of comparison with 1.5 and 2.0 θ_p, larger strain is occurred in the specimen made of the higher strength steel. Therefore, large θ_p produces large absolute amount of incremental deformation to θ_p. As a result, the difference of plastic deformation capacity was observed.

Table 4 – List of test results

Steel grade	Displacement amplitude	$_eK$ [kN-m/rad.]	$_cK$ [kN-m/rad.]	$_eK/_cK$	M_{max} [kN-m]	$_bM_p$ [kN-m]	$M_{max}/_bM_p$	N_u	N_f	η_u	η_f	Fracture mode
400MPa steel	±1.51θ_p	165,500	140,000	1.18	+925 -1007	915	+1.01 1.10	+101c -102c	+107c	289	312	Fracture of beam-flange
	±2.02θ_p	159,600		1.14	+944 -1056		+1.03 -1.15	-37c	-39c	147	159	
490MPa steel	±1.33θ_p	149,800	140,000	1.07	+1012 -1091	1108	+0.91 -0.98	-86c	-94c	220	246	
	±1.53θ_p	142,200		1.02	+1098 -1154		+0.99 -1.04	+62c -59c	-64c	182	191	
	±2.04θ_p	143,600		1.03	+1138 -1226		+1.03 -1.11	-17c	-18c	65	73	
590MPa steel	±1.11θ_p	165,500	152,000	1.09	+1516 -1615	1676	+0.90 -0.96	+57c -53c	-64c	115	142	
	±1.15θ_p	150,800	150,000	1.01	+1495 -1577		+0.89 -0.94	+34c -31c	+38c	80	87	
	±1.19θ_p	159,600	152,000	1.05	+1548 -1689		+0.92 -1.01	+25c -22c	+33c	52	80	
	±1.39θ_p	158,100	150,000	1.05	+1600 -1701		+0.95 -1.01	+11c -13c	+14c	31	39	
	±1.84θ_p	154,900		1.03	+1695 -1784		+1.01 -1.06	+5c -5c	+6c	17	20	

θ_p: Plastic rotation angle, $_eK$: Experimental value of elastic stiffness, $_cK$; Theoritical value of elastic stiffness, M_{max}: maximum moment, N_u: Loading cycle until peak load decresed 10% from maximum load, N_f: Loading cycle until fracture (fracture life), η_u: Cumulative plastic deformation until N_u, η_f: Cumulative plastic deformation until N_f

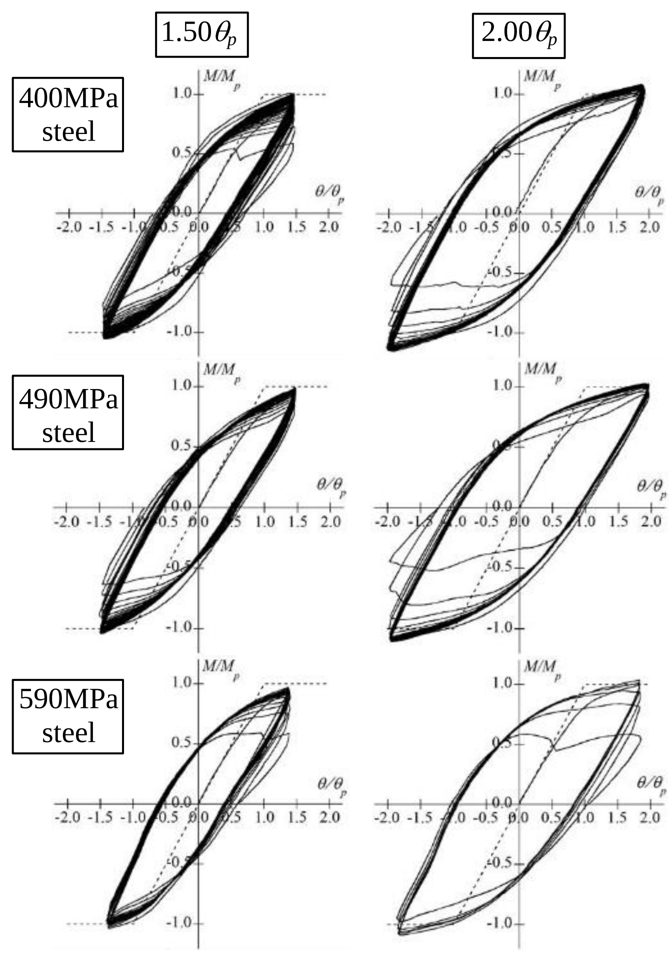


Fig. 6 – M / M_p - θ / θ_p rerationship

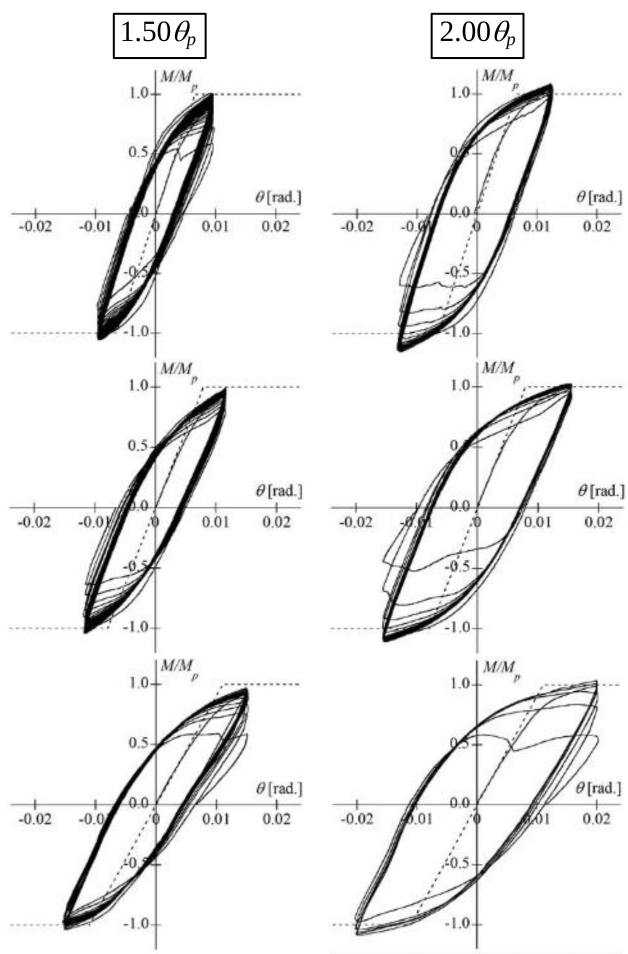
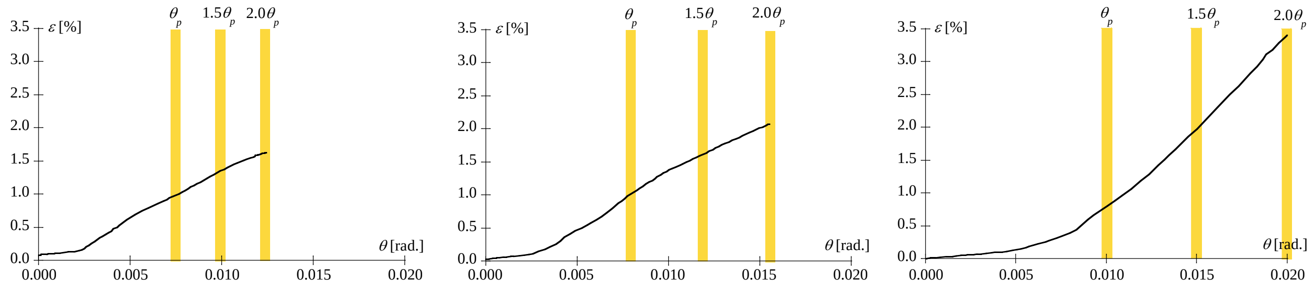


Fig. 7 – M / M_p - θ relationship



(a) 400MPa steel (b) 490MPa steel (c) 590MPa steel

Fig. 8 – Strain history of the beam-end flange in tensile side

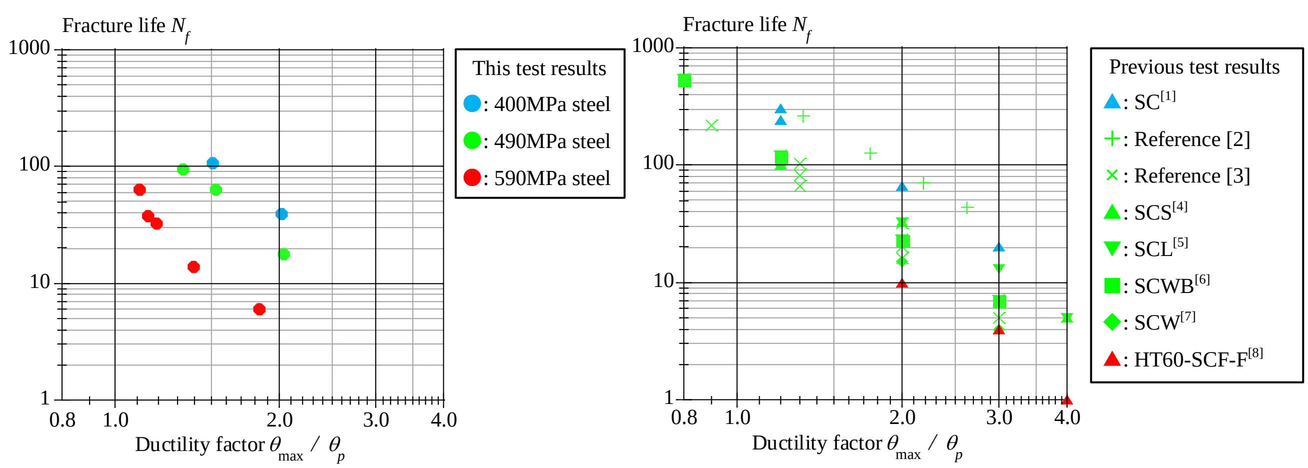


Fig. 9 – Low cycle fatigue characteristics based on the ductility factor[1]~[8]

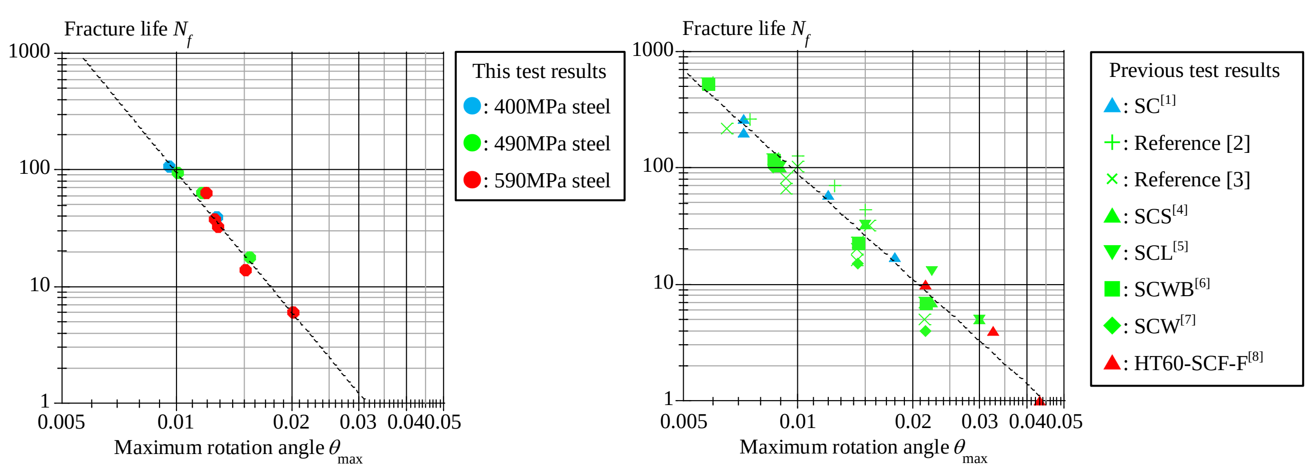


Fig. 10 – Low cycle fatigue characteristics based on the maximum rotation angle[1]~[8]

3.2 Low cycle fatigue characteristics based on the maximum rotation angle $\theta_{\max}$

The low cycle fatigue characteristics based on ductility factor of this test and previous test results [1]~[8] is shown in Fig. 9. Here, the previous test results are summarized in Table 5. They are plotted with fracture life N_f as the vertical axis and ductility factor $\theta_{\max}$ / θ_p as the horizontal axis. In the case of the low cycle fatigue characteristics based on the ductility factor, the plastic deformation capacity of the specimen of large θ_p is low. On the other hand, the low cycle fatigue characteristics based on the maximum rotation angle $\theta_{\max}$, the absolute rotation, of this test and the previous test results [1]~[8] is shown in Fig. 10. It means that the horizontal axis of

Fig.9, the ductility factor θ_{max} / θ_p, is changed to the maximum rotation angle θ_{max}. In the case of the low cycle fatigue characteristics based on the maximum rotation angle θ_{max}, the differences in the plastic deformation capacity of each specimen is decreased. In other word, the plastic deformation capacity of 590MPa steel is almost the same as that of the specimens with made of the other steel.

Table 5 – List of previous test results

Series of specimen	Steel grade	Bean span L [mm]	Bean section [mm]	Sear span ratio L / D	Beam-end connection type	σ_y , σ_u [N/mm^2]	${}_bM_p$ [kN-m]	${}_jM_u$ [kN-m]	${}_jM_u$ / ${}_bM_p$	cK [kN-m/rad.]	θ_p [rad.]	θ_{max} / θ_p	θ_{max} [rad.]	N_u [cyc.]	N_f [cyc.]	Reference number
SC	400MPa	2,017	RH400x200	5.0	Shop welding	277 / 421	374	487	1.30	62,300	0.0060	1.2A	0.0072	202	241	[1]
												1.2B	0.0072	262	302	
												2.00	0.0120	58	66	
												3.00	0.0180	17	20	
–	490MPa	2,050	RH600x200	3.4	Shop welding	345 / 531	1,054	1,337	1.27	185,000	0.0057	1.32	0.0075	-	266	[2]
												1.75	0.0100	-	126	
												2.19	0.0125	-	70	
												2.63	0.0150	-	44	
G	490MPA	3,000	BH600x200	5.0	On-site welding	337 / 511	1,077	1,263	1.16	152,000	0.0072	0.90	0.0065	187	216	[3]
												1.30	0.0093	51	67	
												2.00	0.0143	13	16	
												3.00	0.0215	4	5	
K					Shop welding			1,392	1.28			1.30	0.0093	60	82	
												2.00	0.0143	15	20	
												3.00	0.0215	5	7	
GL	490MPa	4,100	BH800x300	5.1	On-site welding	357 / 512	3,356	4,075	1.21	454,000	0.0077	1.30	0.0100	103	103	
												2.00	0.0154	31	32	
SCS	490MPa	2,492	RH500x200	5.0	Shop welding	351 / 547	740	974	1.32	103,000	0.0075	1.20	0.0090	89	100	[4]
												2.00	0.0150	31	33	
												3.00	0.0225	6	7	
												4.00	0.0300	4	5	
SCL	490MPa	3,770	BH800x300	4.7	Shop welding	340 / 508	3,130	3,926	1.25	437,000	0.0075	1.20	0.0090	98	106	[5]
												2.00	0.0150	31	33	
												3.00	0.0225	-	13	
												4.00	0.0300	-	5	
SCWB	490MPa	2,492	RH500x200	5.0	On-site welding	352/525	739	846	1.14	103,000	0.0073	0.80	0.0058	428	531	[6]
												1.20	0.0086	105	119	
												2.00	0.0144	19	23	
												3.00	0.0216	-	7	
SCW	490MPa	2,325	RH500x200	4.7	Shop welding	368 / 553	774	882	1.14	108,000	0.0074	1.20	0.0086	88	101	[7]
												2.00	0.0144	15	15	
												3.00	0.0216	3	4	
HT60-SCF-F	590MPa	1,200	BH200x100	6.0	Shop welding	445/610	105	118	1.12	10,000	0.0108	2.00	0.0217	-	10	[8]
												3.00	0.0325	-	4	
												4.00	0.0433	-	1	

4. Conclusion

In this paper, cyclic loading tests focusing on suggesting an appropriate evaluation method of plastic deformation capacity of WBFW type connections were carried out. The test results can be summarized as follows: (1) the beam-end connection made of 590MPa steel was fractured during the 14th loading cycle of constant rotation angle $1.5\theta_p$, although that of the 400MPa steel showed sufficient plastic deformation capacity (over 100 cycles) under the same ductility factor; (2) the plastic deformation capacity of the 590MPa steel was almost the same as that of other steel grades regarding the evaluation of low cycle fatigue characteristics based on the maximum rotation angle θ_{max}; (3) finally, the low cycle fatigue characteristics based on the maximum rotation angle θ_{max} was also effective for previous researches with various test condition such as steel grade, beam span and beam section.

5. Acknowledgement

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6. References

[1] Suita K, Hashida I, Sato A (2009): Deformation capacity evaluation of welded beam to column connection subjected to repeated plastic strain (Part 1: Cyclic loading test and crack growth characteristics). *Summaries of Technical Papers of Annual Meeting in Kinki Branch of AIJ*, 393-396, Osaka, Japan (in Japanese).

[2] Watanabe S, Miki N, Jiao Y, Yamada S (2013): Test on beam connection under small amplitude loading history (Part 1: Program of experiments and results of experiments). *Summaries of Technical Papers of Annual Meeting of AIJ*, 807-808, Hokkaido, Japan (in Japanese).

[3] Building Research Institute (2014): Study on seismic performance for super-high-rise steel building against long-period earthquake ground motions. *Building Research Data*, No.160, (in Japanese).

[4] Takatsuka K, Manabe Y, Suita K, Tanaka T, Tsukada T, Su Z (2012): Effect of weld access hole on deformation capacity (Part 2: Deformation capacity of welded beam-to-column connection subjected to repeated plastic strain). *Journal of Structural and Construction Engineering of AIJ*, No. 77, 453-459, (in Japanese).

[5] Takatsuka K, Suita K, Tanaka T, Umeda T (2014): Effect of beam section size and connection detail on deformation capacity (Part 4: Deforamation capacity of welded beam-to-column connection subjected to repeated plastic strain). *Journal of Structural and Construction Engineering of AIJ*, No. 79, 315-321, (in Japanese).

[6] Umeda T, Takatsuka K, Suita K, Tsuji M (2014): Deformation capacity of WBFW moment connection with low strength web connection (Part 17: Deformation capacity evaluation of welded beam-to-column connection subjected to repeated plastic strain). *Summaries of Technical Papers of Annual Meeting of AIJ*, 707-708, Hyogo, Japan (in Japanese).

[7] Asakura N, Tanaka T, Uozumi N, Suita K, Takatsuka K (2014): Cyclic loading tests on H-beams with scallops and weak joint strength (Part 19: Deformation capacity evaluation of welded beam to column connection subjected to repeated plastic strain). *Summaries of Technical Papers of Annual Meeting of AIJ*, 711-712, Hyogo, Japan (in Japanese).

[8] Iyama J, Suzuki T, Kuwamura H (1997): Relation between cyclic and monotonic behavior of steel member. *Summaries of Technical Papers of Annual Meeting in Kanto Branch of AIJ*, No.22, 85-88, Japan (in Japanese).