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Fatigue behavior of steel reinforced concrete (SRC) beams with different shear span-to-depth ratios

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ABSTRACT

There is an increase in the use of steel reinforced concrete (SRC) beams in high-speed railway platforms and bridges that are subjected to fatigue loading. It was found by the authors in their previous research on SRC beams under fatigue loading that flexural fatigue failure was the dominating failure mode when a large shear span-to-beam depth ratio (λ) of 2.63 was used. Research on reinforced concrete (RC) beams under fatigue loading and research on SRC beams under static loading revealed that shear failure may dominate when the shear span-to-beam depth ratio gets smaller. It is unknown if shear fatigue failure will happen in SRC beams with smaller shear span-to-beam depth ratio. This paper presents an experimental investigation of fatigue behavior of SRC beams with shear span-to-beam depth ratio of 1.8, 1.5, 1.1 and 1.0. It was found that shear fatigue failure did not occur in all twenty-seven SRC beams tested even for λ ratio as low as 1.0. Because the failure mode is found to be the same (i.e. dominated by flexural fatigue failure) for all the SRC beams with λ ranging from 1.0 to 2.63, the test results of all 39 SRC beams under fatigue loading were grouped together to derive fatigue strength curves for SRC beam design.

1. Introduction

Steel reinforced concrete (SRC) beams, which consist of a steel section (e.g. H-steel section) embedded inside a reinforced concrete beam, are increasingly used in platforms and bridges in high-speed railway network [1–3]. There is a need to understand the fatigue behavior of SRC beams in order to ensure the safety of high-speed railway infrastructure.

The behavior of steel-concrete composite beams (e.g. reinforced concrete (RC) beams and SRC beams) depends on the shear-span-to-beam depth ratio. There are extensive research on RC beams subjected to fatigue loading (e.g. [4–10]). Two failure modes were observed for RC beams in the literature, namely flexural fatigue failure and shear fatigue failure. The major features of shear fatigue failure for RC beams can be summarized as follows (e.g. [4,6]). The main diagonal concrete crack appears in shear span region and propagates toward the loading point and support. Fatigue fracture occurs in the web reinforcements (including stirrups and bent-up bars) and tensile reinforcements intersecting with the main diagonal concrete. Concrete in shear-compression zone fails due to fatigue. Shear span-to-beam depth ratio (λ) plays a significant role in fatigue failure mode of RC beams. According to the value of λ, shear fatigue failure mode of RC beams can be subdivided into three types, that is, diagonal-compression failure (when λ is no more than 1.0), shear-compression failure (when λ is no less than 1.5) and diagonal-tension failure (when λ is no less than 3.0).

Research on SRC beams under static loading (e.g. [11–16]) revealed that there are also two possible failure modes, i.e. flexural failure and shear failure depending on the shear span-to-beam depth ratio. The main features of shear static failure mode of SRC beams can be described as: In shear span region, concrete cracks diagonally, stirrups yield and even fracture, and web of H-steel yields or buckles.

Both experimental and numerical studies have been carried out by the authors ([17,18]) on the fatigue behavior of SRC beams with a shear span-to-beam depth ratio (λ) of 2.63. Only flexural fatigue failure mode was observed in [17,18]. There is a lack of understanding of the fatigue behavior of SRC beams with shorter λ ratios, which may cause shear fatigue failure as with RC beams under fatigue loading and SRC beams under static loading. This paper fills this knowledge gap.

In order to investigate the fatigue failure modes of SRC beams with shorter shear span-to-beam depth ratio (λ), a total of twenty-seven SRC beams were tested under fatigue loading. The λ ratio varies from 1.0 to 1.8. The other key parameters include steel ratio of H-steel component

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Nomenclature

C	the intercept of *S-N* curve
L	net span of SRC beam
M_{max}	the maximum section bending moment induced by the load P_{max}
M_u	calculated ultimate bending moment for SRC beam
M_y	calculated yield bending moment for pure H-steel beam when stress in the extreme fiber of flange reaches yield strength
N	the number of cycles
N_1	the number of cycles after fracture of the first tensile reinforcement
N_2	the number of cycles after fracture of the second tensile reinforcement
N_f	the number of cycles to failure of specimen
P	the load provided by the actuator
P_{max}	the maximum load applied on specimen
P_{min}	the minimum load applied on specimen
SD	the standard deviation for lg$N$
V_{max}	the maximum section internal force induced by the load P_{max}
V_{min}	the minimum section internal force induced by the load P_{min}
V_u	calculated ultimate shear force for SRC beam
V_y	calculated yield shear force for pure H-steel beam when stress at the section neutral axis reaches yield strength
a	shear span of specimen, i.e. the distance between support and the nearest concentrated load of specimen
f_{cu}	cubic compressive strength of concrete
h	total beam height
m	the negative inverse of slope of *S-N* curve
n_0	the number of cycles corresponding to $\Delta\sigma_0$ before fracture of the two tensile reinforcements
n_1	the number of cycles corresponding to $\Delta\sigma_1$ between fracture of the two tensile reinforcements
n_2	the number of cycles corresponding to $\Delta\sigma_2$ after fracture of the two tensile reinforcements
n_i	the number of cycles corresponding to $\Delta\sigma_i$ under the *ith* stage
$\Delta\sigma$	the stress range
$\Delta\sigma_0$	the stress range of tensile flange of H-steel inside SRC beams before fracture of the two tensile reinforcements
$\Delta\sigma_1$	the stress range of tensile flange of H-steel inside SRC beams after fracture of the first tensile reinforcement
$\Delta\sigma_2$	the stress range of tensile flange of H-steel inside SRC beams after fracture of the second tensile reinforcement
$\Delta\sigma_i$	the nominal stress range under the *ith* stage
ε_{max}	the maximum strain
λ	shear-span-to-beam depth ratio
ξ	steel ratio of H-steel for SRC beam
ψ	steel ratio of tensile reinforcements for SRC beam

Table 1
Parameters of SRC beams and pure H-steel beams.

Beam type	Group No.	Beam designation	Section of H-steel (mm)	Shear span-to-depth ratio λ	Steel ratio of H-steel ξ (%)	Steel ratio of tensile reinforcements ψ (%)	Concrete grade	Load range			
								V_{min} = (1/2) P_{min} (kN)	V_{max} = (1/2) P_{max} (kN)	V_{max}/V_u	M_{max}/M_u
SRC beam	1	B-1.5-5-60-1	H200 × 100×6 × 8	1.5	5.01	0.42	C60	21.0	116.5	0.389	0.396
		B-1.5-5-60-2	H200 × 100×6 × 8	1.5	5.01	0.42	C60	21.0	123.0	0.411	0.419
		B-1.5-5-60-3	H200 × 100×6 × 8	1.5	5.01	0.42	C60	21.0	129.0	0.431	0.439
		B-1.5-5-60-4	H200 × 100×6 × 8	1.5	5.01	0.42	C60	21.0	135.5	0.453	0.461
		B-1.5-5-60-5	H200 × 100×6 × 8	1.5	5.01	0.42	C60	21.0	141.5	0.473	0.481
	2	B-1.5-6-60-1	H200 × 100×6 × 12	1.5	6.40	0.42	C60	25.0	150.0	0.519	0.436
		B-1.5-6-60-2	H200 × 100×6 × 12	1.5	6.40	0.42	C60	25.0	156.0	0.540	0.453
		B-1.5-6-60-3	H200 × 100×6 × 12	1.5	6.40	0.42	C60	25.0	162.5	0.562	0.472
		B-1.5-6-60-4	H200 × 100×6 × 12	1.5	6.40	0.42	C60	25.0	168.5	0.583	0.490
		B-1.5-6-60-5	H200 × 100×6 × 12	1.5	6.40	0.42	C60	25.0	174.5	0.604	0.507
	3	B-1.5-7-60-1	H200 × 100×6 × 16	1.5	7.79	0.42	C60	16.5	162.0	0.579	0.376
		B-1.5-7-60-2	H200 × 100×6 × 16	1.5	7.79	0.42	C60	16.5	168.5	0.602	0.391
		B-1.5-7-60-3	H200 × 100×6 × 16	1.5	7.79	0.42	C60	16.5	174.5	0.624	0.405
		B-1.5-7-60-4	H200 × 100×6 × 16	1.5	7.79	0.42	C60	16.5	181.0	0.647	0.420
		B-1.5-7-60-5	H200 × 100×6 × 16	1.5	7.79	0.42	C60	16.5	187.0	0.669	0.434
	4	B-1.5-5-40-1	H200 × 100×6 × 8	1.5	5.01	0.42	C40	21.0	116.5	0.418	0.403
		B-1.5-5-40-2	H200 × 100×6 × 8	1.5	5.01	0.42	C40	21.0	123.0	0.441	0.425
		B-1.5-5-40-3	H200 × 100×6 × 8	1.5	5.01	0.42	C40	21.0	129.0	0.463	0.446
		B-1.5-5-40-4	H200 × 100×6 × 8	1.5	5.01	0.42	C40	21.0	135.5	0.486	0.468
		B-1.5-5-40-5	H200 × 100×6 × 8	1.5	5.01	0.42	C40	21.0	141.5	0.508	0.489
	5	B-1.0-5-60-1	H200 × 100×6 × 8	1.0	5.01	0.42	C60	21.0	162.5	0.463	0.369
		B-1.0-5-60-2	H200 × 100×6 × 8	1.0	5.01	0.42	C60	21.0	168.5	0.480	0.382
		B-1.0-5-60-3	H200 × 100×6 × 8	1.0	5.01	0.42	C60	21.0	175.0	0.499	0.397
		B-1.0-5-60-4	H200 × 100×6 × 8	1.0	5.01	0.42	C60	21.0	181.0	0.516	0.411
		B-1.0-5-60-5	H200 × 100×6 × 8	1.0	5.01	0.42	C60	21.0	187.5	0.534	0.425
	6	B-1.1-5-50	H270 × 140×8 × 10	1.1	5.54	0.38	C50	30.0	225.0	0.406	0.416
		B-1.8-5-50	H270 × 140×8 × 10	1.8	5.54	0.38	C50	70.0	190.0	0.433	0.564
Pure H-steel beam	N/A	S1	H200 × 100×6 × 12	2.3	N/A	N/A	N/A	N/A			
		S2	H270 × 140×8 × 20	2.3							
		S3	H270 × 140×8 × 20	2.3							
		S4	H270 × 140×8 × 20	2.3							

Note: (*a*) V_{min} and V_{max} are the minimum and maximum section shear forces induced by the load P_{min} and P_{max}, respectively. (*b*) M_{max} is the maximum section bending moment. (*c*) V_u and M_u are the calculated ultimate shear force and bending moment, respectively.