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Fatigue analysis of crumble rubber concrete-steel composite beams based on XFEM

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Abstract. The fatigue fracture of studs is the main reason for failure of composite beams based on massive engineering practices. Hence, studying the laws of cracks initiation and propagation are of great directive significance. eXtended Finite Element Method (XFEM) is an effective method in solving moving discontinuous problems in recent years. This paper extends our recent work on the fatigue damage analysis of stud shear connectors in the steel and crumble rubber concrete (RRFC) composite beams based on XFEM. The process of crack initiation to failure of the stud is simulated and an effective calculation criteria for the fatigue life of the composite beams is put forward. After the reliability of the numerical analysis is verified based on tests results, the extensive parametric study is conducted concerning effects of different rubber contents, shear connection degrees and the stress amplitudes. Results show that with the increasing rubber contents and shear connection degrees, the fatigue lives of composite beams increase obviously. Furthermore, the relationship between the fatigue life of the stud at the edge of the shear span and the whole composite beams is studied. Finally, the S-N curves of the single stud and the whole composite beams are put forward based on XFEM.

Keywords: crumble rubber concrete; extended finite element method; push-out test; composite beams; studs; crack; fatigue life

1. Introduction

Steel-concrete composite beams have been widely used in bridge and building structures for its strong bearing capacity and superior seismic performance, at the same time, its fatigue problem becomes a hot issue. A large amount of engineering practice shows that the fatigue failure mainly comes from the shear connectors who transfer the longitudinal shear force at the interface between steel beam and concrete slab (Nie 2005). Nowadays, the fatigue behavior of shear studs and the whole composite beams mainly based on experimental investigations (Hanswille *et al*. 2007, Nie and Wang 2012, Sohel *et al*. 2012, Papastergiou and Lebet 2014, Wang *et al*. 2014). Besides experimental studies, numerical analysis proves an alternative to the tests and gives reasonably results with less cost and time. Moreover, the more comprehensive measured points can be obtained in numerical analysis. Thus, this more efficient method starts to cause widely value in recent years. Hanswille *et al*. (2007) analyzed the resistance of head studs subjected to fatigue loading. Harnatkiewicz *et al*. (2011) investigated the fatigue behavior of the composite dowel shear connection. Liu and Roeck (2009) studied the fatigue-life-cycle design method of the shear studs and composite bridges. Mirza and Uy (2010) simulated the behavior of the shear connection in the composite beams by ABAQUS. Hou *et al*. (2012) analyzed the dynamic characteristics and shear connector damage identification method of steel-concrete composite beam. Ju and Zeng (2015) investigated the fatigue strength and fatigue damage form of shear stud in steel-concrete composite structures. The numerical analysis performed by the researchers mentioned above are all using S-N curve method and also all the national codes recommend this method (Eurocode 4 1997, Ministry of Construction of China 2003, AASHTO LRFD 2004). The S-N method comes from the metal fatigue calculation. The stresses of the shear stud can be obtained based on FEM analysis, and according to the available S-N curves, the fatigue life N can be calculated.

However, under fatigue loads, the repeated cycles of tension and compression stresses result in the initiation and propagation of cracks on studs. The combined action of steel beam and concrete slab fails when the studs are broken, so studying the laws of cracks initiation and propagation are of great directive significance to practical engineering.

XFEM (eXtended Finite Element Method) is an effective method in solving moving discontinuous problems in recent years. XFEM is introduced by Belytschko and Black (1999) based on the partition of unity method of Melenk and Babuška (1995). It is a mesh-independent method by insert two enrichment functions for fracture modeling. Heaviside function is used to represent displacement jump across crack face and the crack tip asymptotic function is added to model singularity. In XFEM, level set method is used for locating a crack. The

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crack propagation path can go through inside the mesh. XFEM method makes the defining of the crack initiation or propagation of an existing crack easy to realize. Thus, XFEM is a very convenient method to simulate cracking problem without mesh generation as the crack propagating. Nowadays, XFEM has been used in fatigue crack analysis of aircraft wing structures and other complicated crack problems (Pais 2011, Mose *et al*. 1999, Daux *et al*. 2000, Dolbow *et al*. 2000, 2001, Moës and Belytschko 2002, Sukumar *et al*. 2000, Ru *et al*. 2011, Ramazani *et al*. 2016, Pang *et al*. 2016). However, XFEM has rarely been used in the composite beam structure.

To this end, this paper will focus on the fatigue behavior numerical study of shear studs and composite beams based on XFEM. We have systematically conducted the experimental work on push-out specimens and the whole composite beams with crumble rubber concrete (RRFC) (Han *et al*. 2015, 2016, Xing *et al*. 2016). According to the previous research, RRFC has strong capacity of deformation, good crack resistance (Yang and Zhu 2010) and superior anti-fatigue performance. This XFEM numerical study aims to give researchers a better understanding concerning the fatigue lives of the shear studs in different rubber mixed concrete during the push-out test procedure and the fatigue lives of the whole composite beams. Our results shows that with the increasing rubber content, the fatigue lives of single stud and the whole composite beam increase. Moreover, the S-N curve of the whole composite beam is put forward based on XFEM.

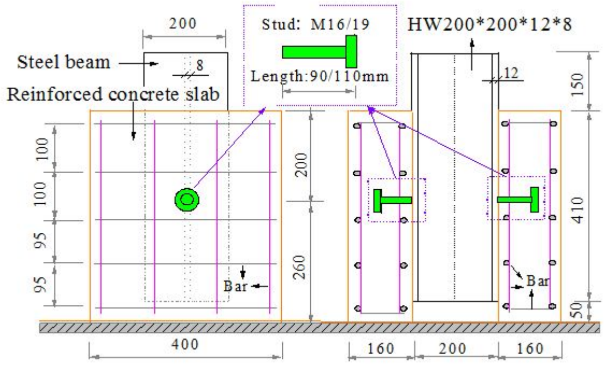
In this paper, the fatigue behavior of shear stud is studied through push-out model used XFEM in ABAQUS. The verification of the numerical result is presented through comparison with our previous test results in Section 2. Furthermore, the parametrical study concerning the different rubber contents, the stud dimensions and the stress amplitudes are also presented in this part. Section 3 shows the fatigue damage simulations of the whole composite beam and the comparison of simulation results and test ones. After that the parametrical study is analyzed. Discussion and some concluding remarks of this paper are shown in Sections 4 and 5, respectively.

2. Numerical analysis on shear studs using XFEM

In this section, the XFEM method is used to analyze the shear studs in push-out test model. The numerical analysis work is carried out based on our previous experimental work on push-out specimens and the simulation results can be verified based on previous test results (Han *et al*. 2016). The crack initiation and propagation in the root of stud are simulated and the fatigue lives of studs are analyzed based on parametrical study.

2.1 The XFEM numerical model and the calculation parameter selection

The geometry of the specimen is shown in Fig. 1. The section of the rolled H-section steel beam is 200 mm × 200 mm × 8 mm × 12 mm and the length is 560 mm. The size of concrete is 460 mm × 400 mm × 160 mm. The diameter of reinforced bar is 10 mm. In order to obtain accurate results from the numerical analysis, all components in the shear connection must be properly modelled. The main components are concrete slab, steel beam, shear studs and reinforced bar. Nonlinear material constitutions and concrete damage plasticity models are established in the analytical investigation. Moreover, the reasonable finite element type mesh generation and contact algorithms are adopted.



(a) Front view (b) Side view

Fig. 1 Push-out test specimen (Han *et al*. 2015)

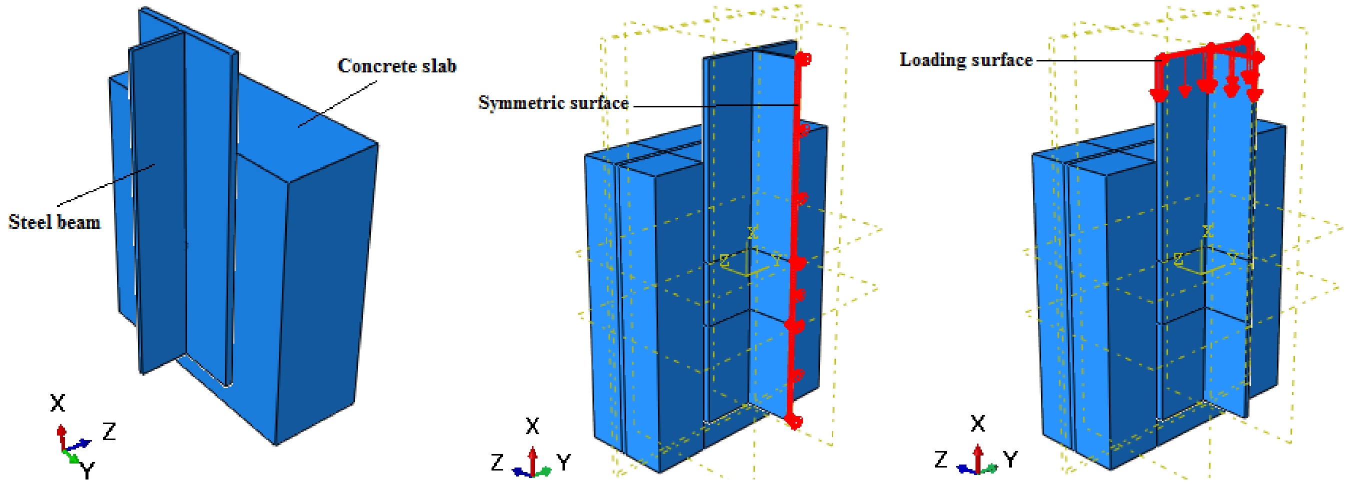
2.1.1 Finite element type and mesh

Due to the symmetry of the specimen, only a half of the push-out test is modeled, shown in Fig. 2(a). The concrete slab, steel beam and shear stud are all meshed with solid element C3D8R and reinforced bar used Truss element. In order to achieve the accurate results, the same mesh generations are applied on the interaction part for different components, such as the bottom of the studs and the corresponding part of steel beam, also the contact surface of studs and concrete. Studs and its nearby place used the smallest mesh size 1 mm. To reduce the analysis time, the size of non-critical part is larger and the largest mesh size is 20 mm.

2.1.2 Interaction and constrain connections

The interactions of steel concrete, concrete and studs in push-out modeling are the most important and difficult part. Six interactions are included in this analysis.

Sliding friction is adopted between the surface of the stud shank and the concrete inner surfaces and the coefficient of friction is 0.2. The same interaction method as stud and concrete surfaces is used between steel flange and corresponding concrete slab. An equal dimension of stud circle is cut in the corresponding place of steel flange and these two parts are tied to each other. This may bring difficulties in meshing, while the results can be more accurate, as the nodes on the surfaces of stud bottom and steel flange are consistent with the same mesh. According to the removed studs from the concrete slab in broken specimens after the push-out tests, no deformation is found in the head of stud. Moreover, the stud head is anchored in concrete slab and the stud shank is equivalent to a beam fixedly constrained on both ends (Han *et al*. 2015). Thus, the head of stud is merged together with the concrete slab in



(a) Simulation model (b) Symmetric boundary (c) Loading surface

Fig. 2 Push-out test specimen

this numerical analysis. The stud shank is tied to the stud head and the stud head is merged together with concrete slab. Rebar is embedded in concrete slab.

2.1.3 Loading and boundary conditions

The symmetric boundary condition is applied to the surface at the symmetric planes of the specimen as shown in Fig. 2(b). The displacement of Z direction is zero. The displacement of X direction on the bottom of the concrete slab is fixed and Y direction is fixed at the foot point. The loading applied on the top surface of steel beam according to the push-out tests, shown in Fig. 2(c). The fatigue cyclic loading is applied through defining the load ramp.

2.1.4 Material properties

Concrete

Different crumb rubber contents and concrete strengths were taken into consideration in our previous tests and four different material properties were obtained (Han *et al.* 2015). The concrete damage plasticity model in ABAQUS material library was adopted here. In this material model, yielding arts of the stress-strain curve of the concrete are treated separately for tension and compression. The concrete damage plasticity model assumes a non-associated potential plastic flow. According to the stress-strain curves tests and other material properties test results (Han *et al.* 2015), the material dilation angel and eccentricity were taken as 45 and 0.1, respectively. The ratio of biaxial compressive strength to the uniaxial compressive strength (f_{b0}/f_{c0}) was taken as 1.16. K was 0.667 and viscosity parameter was 0.

Steel beam, reinforcement and shear studs

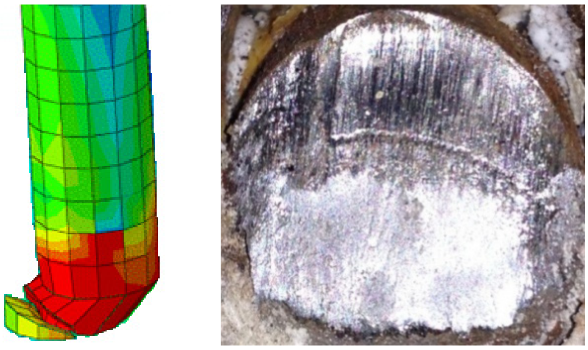
The stress-strain relationship of steel beam, reinforcement and shear studs were modeled by the slash-straight curves. The mechanical behaviors for both tension and compression were assumed to be similar. The ultimate strengths of steel beam, shear stud and rebar were 400MPa, 450 MPa and 335 MPa, respectively.

2.1.5 The definition of XFEM crack and the convergence controlling method

In push-out test, the fatigue failure of the stud shank is the main failure mode. Thus, the crack initiation should be defined in the stud material. The damage for traction separation laws "Maxps damage" is used for the damage criteria. In the damage initiation part, the damage initiation tolerance is defined as 0.05 and the maximum principal stress is 22.0e+6 according to the steel material property. When the stress of the stud reaches the maximum stress, the crack initiation begins. In the damage evolution part, the crack propagation according to the energy principle and the normal mode fracture energy is defined as 2870. Several analysis controls can be used to improve the convergence behavior, including set the reasonable minimum and maximum increment sizes for step, increase the number of increments for step from the default value of 100, use numerical scheme applicable to discontinuous analysis and increase value of maximum number of attempts before abandoning increment. Through applying cyclic loading, the crack initiation and propagation, when the crack development completed, the loading time is recorded as the fatigue life of the stud.

2.2 Numerical analysis results and verification

Here PF-5 in Reference Han *et al.* (2016) is used as the simulation example. The stress amplitude is 129.38 MPa according to our previous push-out tests. Correspondingly, the peak and valley values of the fatigue load adopt 76 kN and 24 kN in the numerical simulation, respectively. The fatigue failure situation is shown in Fig. 3(a) based on XFEM numerical simulation. It can be seen that the crack initiation occurs near the root of the stud where the maximum principle stress takes place. The crack propagation ends at the interface of the stud's root and the steel beam. The stress of the crack splitting part is small, and the remaining part of the stud is under higher stress. When the rest of the stud's cross section can't bear the peak fatigue loading, the fatigue failure happens. Thus, the



(a) XFEM simulation results (b) The fatigue failure section of the test

Fig. 3 The comparison of stud fracture between the numerical simulation results and test ones

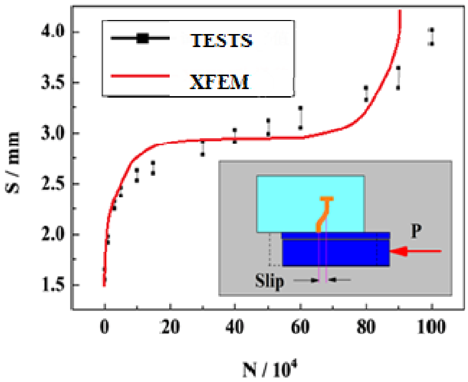


Fig. 4 The dynamic slip of the shear stud between XFEM simulation and test results

fatigue failure surface of the stud can be divided into fatigue crack growth area and static shearing area. Moreover, the fatigue crack grows area is about a third of the cross-section of the stud, which shows a good agreement with the previous test results, shown in Fig. 3(b).

According to the loading process, when the crack propagation ends, the loading time 91.4 (unit 10^4), is the fatigue life of stud, and our test result is 101.79 (unit 10^4). The relative error between the tests and simulation is about 10%. Thus, the XFEM simulation results tend to be credible.

Besides, during the fatigue failure, the stud has plastic deformation and the fatigue damage is ductile. According to our previous investigation (Han *et al*. 2016), the dynamic slip values can reflect the fatigue behavior of the shear stud. The comparison of the dynamic slip of the shear stud between XFEM simulation and test results is shown in Fig. 4. We can see that the trend of the stud's dynamic slip of the stud follows the "Paris Curve". At the beginning, the curves had a remarkable growth, then it turned out to be slower, finally the suddenly failure occurred. It can be seen from Fig. 4 that the numerical results show a good agreement with test ones. After the reliability of the numerical analysis is verified, an extensive parametric study is conducted below concerning effects of rubber contents, stud dimensions and the stress amplitudes.

Table 1 XFEM simulation results of studs' fatigue lives with different rubber content

Rubber content	0%	5%	10%	15%
Fatigue lives (10^4)	68.3	91.4	118.4	139.6
Rising amplitude (%)	--	33.8	73.4	104.4

Table 2 XFEM simulation results of studs' fatigue lives with different studs' diameters

Studs diameters (mm)	16	19	22	25
Fatigue lives (10^4)	91.4	86.1	79.8	72.4
Rising amplitude (%)	--	5.8	12.7	20.8

Table 3 XFEM simulation results of studs' fatigue lives under different stress amplitudes

Stress amplitudes (MPa)	100	115	130	145
Fatigue lives (10^4)	360	178	91	20

2.3 Parametrical study

2.3.1 Effect of rubber contents

The XFEM simulation results of studs' fatigue lives with different rubber content is shown in Table 1. Here, the fatigue load and the stud diameter are kept consistency in each group. The results showed that the fatigue lives of the studs embedded in RRFC with 5%, 10% and 15% rubber content increase 33.8%, 73.35% and 104.4%, respectively. The reason is that the RRFC has better fatigue behavior than ordinary concrete. The studs have more compatible deformation in ductile RRFC. When bearing the fatigue loadings, RRFC can provide more sufficient and longer supporting for shear studs to make it effective to transfer the force. Thus, the fatigue lives of stud increase.

2.3.2 Effect of stud diameters

In this XFEM analysis, the stress amplitudes are kept consistency in each group, meaning the ratio of the load and the cross-section of stud is the same. RRFC with rubber content 5% is used here. Four different diameters of studs are taken into consideration. XFEM simulation results of studs' fatigue lives with different studs diameters is shown in Table 2. The results showed that the fatigue lives of the studs with 19, 22 and 25 mm diameters decrease 5.8%, 12.7% and 20.8%, respectively, compared with 16 mm studs. Thus, the smaller diameter of stud, the longer fatigue life stud has. That is because the restriction of the concrete in larger diameter studs is weaker than small ones. It can be concluded that under the same stress amplitude, the stud with smaller diameter has superior fatigue behavior than larger ones.

2.3.3 Effect of stress amplitudes

Here, 5% rubber content RRFC and stud with 16 mm diameter is adopted. The XFEM simulation results of studs' fatigue lives concerning four different stress amplitudes are shown in Table 3. With the increasing stress amplitudes, the fatigue lives of the studs decrease dramatically. Hence, the stress amplitude is inversely proportional to the fatigue life of studs.

3. Numerical simulation on composite beams using XFEM

Based on the XFEM analysis on fatigue behavior of shear stud in Section 2, the XFEM simulation on fatigue lives of composite beams with RRFC is presented. The numerical analysis process is discussed first. After the reliability of the numerical analysis is verified based on our previous tests results in Reference Xing *et al*. (2016), an extensive parametric study is conducted.

3.1 Numerical model

In this part, the numerical models are built based on FBFT-1 (rubber content 10%) and FBFT-2 (rubber content 0%) in Reference Xing *et al*. (2016). The finite element type, interaction and constrain connections and the material properties are the same with the push-out test model in Section 2. Several equal dimensions of stud circles are cut in the corresponding place of steel flange to make sure the accurate connected relationship, shown in Fig. 5(a). The meshing situation is shown in Fig. 5(b). The test specimen can be treated as a simply supported beam. Hence, in the numerical analysis, the displacements of the *Z* direction (U3) of the both ends are constrained, furthermore, the displacements of the *X* direction (U13) and the rotation of *Y* direction (UR2) on one end is also constrained. The boundary condition and the loading surface are shown in Fig. 6. The loading surface and the supports are defined as rigid material here.

3.2 The fatigue analysis criteria of composite beams

According to our previous experimental studies, the fatigue failure of the composite beams is boils down to the fatigue fracture of the studs at the shear spans of the composite beam. Moreover, the stud at the edge of the shear span bears the maximum fatigue stress, so the fatigue

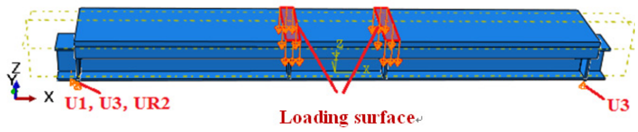
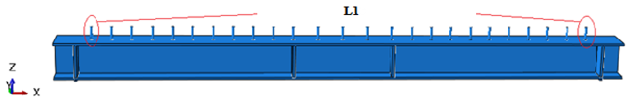
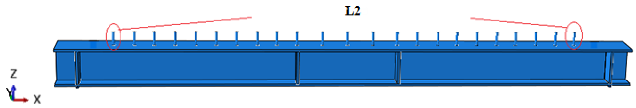


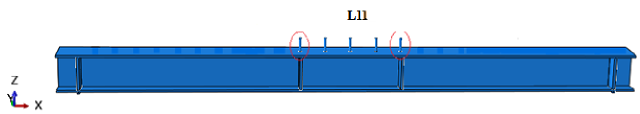
Fig. 6 The boundary condition and the loading surface



(a) Fatigue life L1



(b) Fatigue life L2

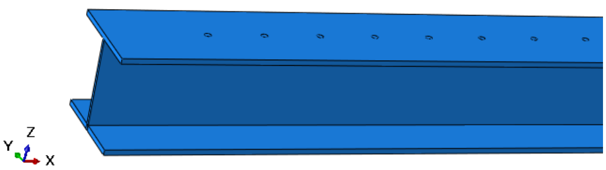


(c) Fatigue life L11

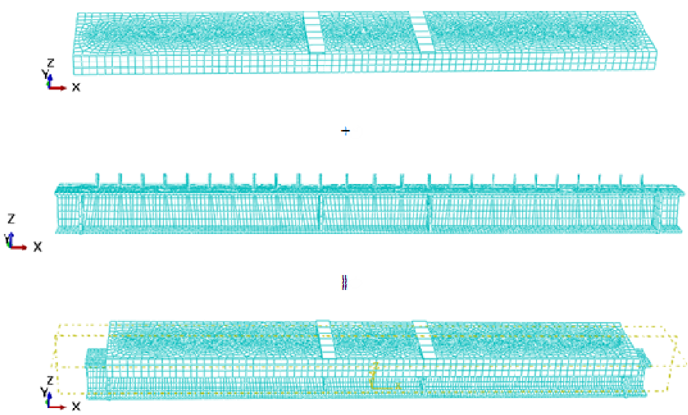
Fig. 7 XFEM fatigue life calculation method of composite beams

fracture happens first in the stud at the edge, and then fracture develops towards the studs in the middle. Hence, the fatigue life of the composite beam is the sum of the fatigue lives of studs at the shear span.

The specific fatigue life calculation method is described below. The XFEM crack is first signed to the two studs in the edge of the shear span. Then the fatigue load apples. When the two cracks propagation end, the loading time is recorded as L1, shown in Fig. 7(a). Then the broken studs are deleted in the new analysis model. The XFEM crack is signed to the stud, which is the second last stud in the primary model, shown in Fig. 7(b). When the crack propagation ends, the loading time is recorded as L2. Then repeat this method, delete the broken stud and sign the crack to the new stud at the edge until all the studs broke at



(a) XFEM simulation resultst



(b) The fatigue failure section of the test

Fig. 5 The numerical model of the composite beams

Table 4 XFEM simulation results on composite beams

FBFT-1 (rubber content 10%)			FBFT-2 (rubber content 0%)		
No.	Number of residual studs	Fatigue lives (10^4)	No.	Number of residual studs	Fatigue lives (10^4)
L1	20	7.958	L1	20	5.482
L2	18	4.459	L2	18	2.983
L3	16	2.492	L3	16	1.463
L4	14	0.843	L4	14	0.652
L5	12	0.583	L5	12	0.352
L6	10	0.312	L6	10	0.164
L7	8	0.186	L7	8	0.068
L8	6	0.059			
Fatigue life of FBFT-1	L = 16.9		Fatigue life of FBFT-2	L = 11.2	

XFEM simulation results on composite beams the shear span. Fig. 7(c) shows the studs at the boundaries of the shear span and the pure bending section and the fatigue life is recorded as L11. Finally, the sum of the L1 to the L11 is the fatigue life of the composite beam.

3.3 XFEM simulation results of the composite beams

According to the aforementioned fatigue analysis criteria, the fatigue calculation process shows in Table 4. The fatigue peak and valley loads are 55 kN and 275 kN, respectively.

According to Table 4, the final fatigue lives of FBFT-1 and FBFT-2 are 16.9 and 11.2 (unit 10^4), respectively. Comparing the test results 15 and 10 (unit 10^4), the relative error is about 12%. Thus, the XFEM simulation results tend to be credible. Both the XFEM analysis and experimental studies prove that the composite beams with RRFC have superior fatigue behavior of composite beams with ordinary concrete. Hence, adding crumb rubber can improve the fatigue fracture of the studs and increase the fatigue life of composite beams.

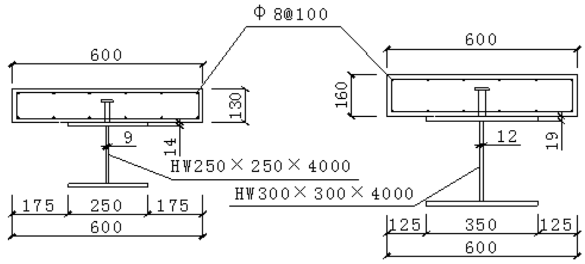
Moreover, we can see that the stud at the edge of the shear span contributes a lot to the whole composite beams. With the increasing number of the broken studs and stress redistribution, the fatigue life of the new stud at the edge decreases due to the larger stress, leading to the fatigue life of the last few studs can be neglected. For FBFT-1, the ignore items are L9 to L11, while FBFT-2 are L8-L11.

3.4 Parametrical study

Here, two types of sectional dimensions (Fig. 8) are concerned according to our fatigue tests (Xing *et al*. 2016). Further-more, the fatigue lives of the stud at the edge of the shear span (L1 aforementioned) are listed in each table for comparison with the fatigue lives of the whole composite beams.

3.4.1 Effect of rubber contents

The XFEM simulation results of fatigue lives of composite beams with different rubber content are shown in Tables 5 and 6. The results showed that the fatigue lives of the composite beams with 5%, 10% and 15% rubber content increase about 20%, 50% and 70%, respectively.



(a) Type 1 (b) Type 2

Fig. 8 Cross sectional of two types of specimens (unit: mm)

Table 5 XFEM simulation results for type 1 composite beams with different rubber

Rubber content	0%	5%	10%	15%
L1 (10^4)	5.5	6.2	8.0	8.6
Fatigue lives (10^4)	11.2	13.6	16.9	18.8

Table 6 XFEM simulation results for type 2 composite beams with different rubber contents

Rubber content	0%	5%	10%	15%
L1 (10^4)	13.7	17.4	21.6	24.2
Fatigue lives (10^4)	30.8	37.3	47.5	52.2

Table 7 XFEM simulation results for type 1 composite beams with different shear connection degrees

Studs diameters (mm)	16	19	22	25
Shear connection degree	0.50	0.71	0.94	1.22
L1 (10^4)	8.0	15.9	31.1	47.1
Fatigue lives (10^4)	16.9	34.7	68.3	102.6

Table 8 XFEM simulation results for type 2 composite beams with different shear connection degrees

Studs diameters (mm)	16	19	22	25
Shear connection degree	0.35	0.50	0.66	0.86
L1 (10^4)	12.8	21.6	35.3	47.3
Fatigue lives (10^4)	26.5	47.5	74.1	90.2

3.4.2 Effects of shear connection degree

The effect of shear connection degree is considered through using four different studs' diameter under the condition of the number of studs unchanged. Tables 7 and 8 show that the XFEM simulation results of fatigue lives of composite beams with shear connection degrees. It can be concluded that with the increasing shear connection degree, the fatigue lives of composite beams increase obviously.

Table 9 XFEM simulation results for type 1 composite beams under different load amplitudes

Load amplitudes (kN)	180	200	220	240
L1 (10^4)	43.5	16.2	8.0	2.4
Fatigue lives (10^4)	100.7	35.6	16.9	5.8

Table 10 XFEM simulation results for type 2 composite beams under different load amplitudes

Load amplitudes (kN)	440	460	480	500
L1 (10^4)	51.5	36.2	21.6	12.4
Fatigue lives (10^4)	109.7	75.6	47.5	24.3

3.4.3 Effect of load amplitudes

Here, 10% rubber content RRFC is adopted. The XFEM simulation results of fatigue lives of composite beam concerning four different load amplitudes are shown in Tables 9 and 10. With the increasing load amplitudes, the fatigue lives of the studs decrease dramatically. Hence, the load amplitude plays a decisive role to the fatigue life of composite beams.

4. Discussion

It can be concluded from Section 2 that with the increasing rubber content, the fatigue lives of the stud increased a lot. Hence, the rubber content is regarded as an impact factor in our fitting equation derived from parametrical study shown as Eq. (1) and m is the rubber content, here m is between 0% and 15%

$$\lg N = 17.85 - \left(\frac{1}{1+m^2}\right) \times 6 \lg \Delta\tau \quad (1)$$

The comparison between numerical simulation results and other researches are shown in Fig. 9. The bottom line of the purple scatter is the fitting equation of 0% rubber content, and the top line is 15% rubber content. It can be

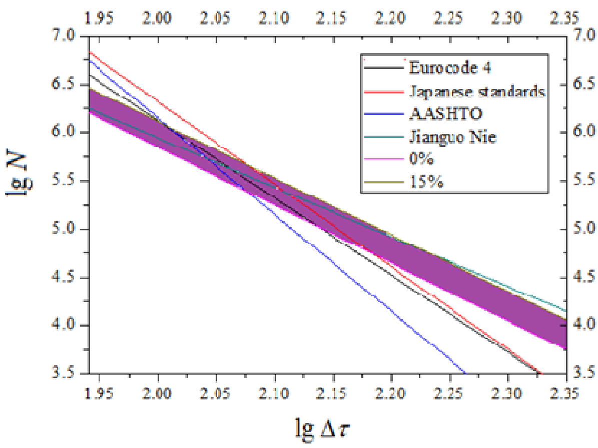


Fig. 9 Comparison between numerical simulation results and other research

seen that the Eurocode 4, Japanese standards and AASHTO LRFD are relatively conservative compared to our results, while Nie's result is safer when the stress amplitude is small.

Nowadays, the S-N curve of the shear connections fitting from push-out tests is written in several national codes. However, there are no corresponding standards for S-N curves of the whole composite beams. That is because the S is very difficult to define and it is not easy to summarize which part is the decisive factor. The authors suggest that the S is still the stress amplitude of the stud. According to our analysis, it can be seen that the stud at the edge of the shear span contributes a lot to the whole composite beams. Thus, the fatigue life of L1, meaning the stud at the edge of the shear span is studied to find the relationship between L1 and the fatigue life of the whole composite beams. According to Section 3, even if the impact factors, including different rubber contents, shear connection degrees, load amplitude or sectional dimension types are changed, the law that the fatigue life of the stud at the edge is nearly half of the whole composite beams is the same. Hence, the S-N curve of the whole composite beam can be regarded as Eq. (2). Here $\Delta\tau$ is the shear stress amplitude of the stud at the edge of the shear span in the composite beams.

$$\lg N = 18.151 - \left(\frac{1}{1+m^2}\right) \times 6 \lg \Delta\tau \quad (2)$$

5. Results

This paper extends our recent work on the fatigue damage analysis of stud shear connectors and the steel and crumble rubber concrete (RRFC) composite beams based on XFEM. The single studs in push-out tests is analyzed and verified first, and the extensive parametric study is conducted concerning effects of different rubber contents, stud dimensions and the stress amplitudes. Before the simulation of the whole composite beams, a calculation criteria is put forward. The relationship between the fatigue life of the stud at the edge of the shear span and the whole composite beams is the key point of this study. Following conclusions have been drawn:

- According to the XFEM simulation of the shear stud, the crack initiation occurs near the root of the stud where the maximum principle stress takes place. The crack propagation ends at the interface of the stud's root and the steel beam. The stress of the crack splitting part is small, and the remaining part of the stud is under higher stress. When the rest of the stud's cross section can't bear the peak fatigue loading, the fatigue failure happens. The relative error between the tests and simulation is about 10%. Thus, the XFEM simulation results tend to be credible. Furthermore, the fatigue failure surface of the stud can be divided into fatigue crack growth area and static shearing area. Moreover, the fatigue crack grows area is about a third of the cross-section of the stud, which shows a good agreement with the previous test results.

- The parametrical study results of single stud from push-out test show that the fatigue lives of the studs embedded in RRFC with 5%, 10% and 15% rubber content increase 33.8%, 73.35% and 104.4%, respectively. Thus, RRFC can provide more sufficient and longer supporting for shear studs. Moreover, the fatigue lives of the studs with 19, 22 and 25 mm diameters decrease 5.8%, 12.7% and 20.8%, respectively, compared with 16 mm studs. Thus, the stud with smaller diameter has superior fatigue behavior than larger ones. Besides, the stress amplitude is inversely proportional to the fatigue life of studs.
- The fatigue life of the whole composite beam is the sum of the fatigue lives of studs at the shear span. The relative error between numerical analysis and test results is about 12%. Thus, the XFEM simulation results tend to be credible.
- The stud at the edge of the shear span contributes a lot to the whole composite beams. With the increasing number of the broken studs and stress redistribution, the fatigue life of the new stud at the edge decreases due to the larger stress, leading to the fatigue life of the last few studs can be neglected.
- According to the parametrical study of the composite beams, the fatigue lives of the composite beams with 5%, 10% and 15% rubber content increase 20%, 50% and 70%, respectively. Moreover, with the increasing shear connection degree, the fatigue lives of composite beams increase obviously. Besides, the load amplitude plays a decisive role to the fatigue life of composite beams.
- The S-N curve of the studs derived from parametrical study is compared with other researches. According to extensive parametric study, it can be concluded that the fatigue life of the stud at the edge is nearly half of the whole composite beams. The S-N curve of the whole composite beam can be obtained from S-N curve of single studs.

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