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# Fatigue behavior of stud shear connectors in steel and recycled tyre rubber-filled concrete composite beams

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**Abstract.** This paper extends our recent work on the fatigue behavior of stud shear connectors in steel and recycled tyre rubber-filled concrete (RRFC) composite beams. A series of 16 fatigue push-out tests were conducted using a hydraulic servo testing machine. Three different recycled tyre rubber contents of concrete, 0%, 5% and 10%, were adopted as main variable parameters. Stress amplitudes and the diameters of studs were also taken into consideration in the tests. The results show that the fatigue lives of studs in 5% and 10% RRFC were 1.6 and 2.0 times greater of those in normal concrete, respectively. At the same time, the ultimate residual slips' values of stud increased in RRFC to highlight its better ductility. The average ultimate residual slip value of the studs was found to be equal to a quarter of studs' diameter. It had also been proved that stress amplitude was inversely proportional to the fatigue life of studs. Moreover, the fatigue lives of studs with large diameter were slightly shorter than those of smaller ones and using larger ones had the risk of tearing off the base metal. Finally, the comparison between test results and three national codes was discussed.

**Keywords:** recycled tyre rubber-filled concrete; rubber content; push-out test; S-N curve; stress amplitude; fatigue lives; residual slip

## 1. Introduction

Recycled tyre rubber-filled concrete (RRFC) is a new type of concrete using recycled tyre rubber as a composition of cement concrete materials. The research history of RRFC has been more than 30 years. The first section of RRFC pavement was built in the campus of Arizona University in 1999 by Prof. Han Zhu and his team (Zhu *et al.* 2007). According to previous research, RRFC has strong capacity of deformation, ductile failure and good crack resistance (Yang and Zhu 2010). Besides, its acoustical properties, wearing resistance, aging resistance and erosion resistance are all better than normal concrete (Zhu *et al.* 2007). Hence, RRFC are extended to use in tennis courts, parking area, bridge deck paving and so on (Eldin and Senouci 1993, Hernadez-Olivares *et al.* 2002). The research on fatigue behavior of RRFC is mainly concentrated in the recent 10 years. Fatigue tests of RRFC samples with 0%, 3.5%, and 5% recycled tyre rubber content were carried out by Hernadez-Olivares *et al.* (2007). Test results showed that the elastic

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modulus of RRFC strengthened under cyclic loading while that of normal concrete was not change. The fatigue damage process of RRFC tested by the acoustic emission technique was carried out by Wang *et al*. (2009). According to the intensities of signals and accumulative hits, RRFC had been proved to have better energy dissipation ability and lower speed of damage process compared with normal concrete. Hence, RRFC has superior anti-fatigue performance (Wang *et al*. 2009).

Steel-concrete composite beam has been widely used in the field of bridge and building structures for decades. As a beneficial result of combining the advantages of steel and concrete components, composite beams bring good economic and social benefits (Nie 2005). As an important component of steel-concrete beam, shear connector transfers the longitudinal shear force at the interface between steel and concrete. Push-out test is proved to be an effective method to determine the ultimate strength, deformation capacity and fatigue lives of shear connectors. A great number of push-out tests were conducted by various researchers to determine the static and fatigue behavior of shear connectors. An and Cederwall (1996) investigated the different behavior of studs between normal strength and high strength concrete through push-out tests, and the results showed that the concrete compressive strength significantly affects the shear capacity of studs. Valente and Cruz (2010) studied the performance of steel and light-weight concrete composite beams to obtain a good behavior similar to that of normal concrete. Zhao and Yuan (2010) conducted several tests on the composite beams with high-strength steel and concrete. Yan *et al*. (2013) carried lots of push-out tests to reveal the influence of three factors, light-weight concrete, concrete strength and J-hook connectors on composite beams. Push-out tests conducted by Su *et al*. (2014) focused on the multi-row studs in high strength concrete. The study of the fatigue behavior of stud connectors has become a hot issue because the fatigue failure of stud connectors happens frequently in the practical engineering. The statues of fatigue behavior of studs are discussed in section 2 together with the design methods in detail.

However, RRFC has never been used as a main structural component in composite beams before. People pay more attention to the bearing capacity of the shear studs, however few researchers have addressed the relationship between the fatigue behavior of shear studs and RRFC. This paper will focus on this point. We have systematically studied the effect of RRFC on the static behavior of shear studs in composite beams based on static push-out tests. Results show that the deformation capacity and ductility of studs improve significantly in RRFC (Han *et al*. 2015a, b, Xing *et al*. 2016).

Due to the superior fatigue behavior of RRFC and based on the validated good effect of static test results, this paper will focused on further study on fatigue behavior of steel-RRFC composite beams. Based on our experiments, the fatigue failure modes of specimens were observed and the impact factors of studs' fatigue lives were investigated. Moreover, the comparison between test results and three national codes was discussed.

## 2. Fatigue calculation methods

In composite beams, shear connectors play an important role in resistance to the longitudinal shear and uplift force to ensure the two key components working together. The most widely used connector is shear stud and its fatigue behavior is studied mainly by push-out test at present. Many researchers found that the damage of shear connectors was the main part in composite beam under fatigue loads and the fatigue calculation methods of the shear connector are introduced below.

The *"S-N curve method"* comes from fatigue calculation of metal materials. Stress amplitude

Table 1 The typical formulas of studs

| Source | Values of coefficient | | Stress amplitude limits (MPa) | | |
|---|---|---|---|---|---|
| | X | Y | N = $10^6$ | N = $2\times10^6$ | N = $10^7$ |
| Nie (2005) | 16.205 | 5.130 | 97.6 | 85.3 | 62.3 |
| Slutter and Fisher (1966) | 16.177 | 5.376 | 78.2 | 69.0 | 50.9 |
| Eurocode 4 (1997) | 22.123 | 8.000 | 103.6 | 95.0 | 77.7 |
| GB50017-2003 (2003) | 12.167 | 3.000 | 113.6 | 90.2 | 52.8 |
| AASHTO LOAD (2004) | 26.150 | 10.000 | 103.5 | 96.6 | 82.2 |

(*S*) can determine its fatigue performance (stress cycle times *N*), which is the main computing form adopted by many national standards. In the following part stress amplitude is represented by $\Delta\tau$.

Slutter and Fisher (1996) found that the fatigue failure occurred in weld zone according to fatigue push-out tests and the calculation formula was given for the first time, shown in Eq. (1)

$$\Delta\tau = 1020 N^{-0.186} \tag{1}$$

Johnson (2000) put forward a formula of studs after summarized the typical research achievements. It only considering the influence of stress amplitude and the formula was adopted by Eurocode 4

$$\lg N + 8\lg\Delta\tau = 22.123 \tag{2}$$

Nie (2005) found that shear stress amplitude was the main influence factors on stud's fatigue lives and fitted out the fatigue life formula under the assurance rate of 95%

$$\lg N + 5.13\lg\Delta\tau = 16.205 \tag{3}$$

Along with the further study of scholars, fatigue calculation formulas of studs are gradually written into many national standards. The typical formula model is summarized below and stress amplitude limits of different stress cycle times are given in Table 1.

Table 2 The parameters of push-out specimens

| Specimens | Concrete strength grade | Rubber content | Size of studs | Reinforcement |
|---|---|---|---|---|
| PF-1~3 | C30 | 0% | M16 | HorizontalΦ10@100 Φ10@95 (1.5%) Vertical Φ10@110 (1.45%) |
| PF-4~6 | | 5% | | |
| PF-7~9 | | 10% | | |
| PF-10~12 | | 0% | M19 | |
| PF-13 | | 10% | | |
| PF-14~15 | | 0% | M22 | |
| PF-16 | | 10% | | |

Typical formula model can be expressed as Eq. (4)

$$\log N = X - Y \log \Delta\tau \tag{4}$$

According to Table 1, the results of Slutter and Fisher are relatively conservative. Eurocode 4 is close to the AASHTO Load when N = $10^6$. While when N = $10^7$, Eurocode 4 become more conservative. The Chinese standard has the largest falling gradient due to the small value of Y but the stress amplitude limit under two million times is relatively reasonable. Nie and Wang (2010) collected and analyzed hundreds of fatigue tests results and the AASHTO Load was proved to have the highest ratio of confidence.

## 3. Fatigue tests program

### *3.1 Test specimens*

According to the Eurocode-4 (1997), a total of 16 specimens were designed. The parameters of push-out specimens are shown in Table 2 and the size of specimen is shown in Fig. 1. The detailed specifications of each component are introduced below:

(a) Steel Beam: The rolled H-section steel beams were used with a size of 200 mm × 200 mm × 8 mm × 12 mm. The material type was Q235B, with yield strength of 235 MPa and ultimate strength of 400 MPa.
(b) Concrete Slab: The size of the concrete slab was 460 mm × 400 mm × 160 mm. The slabs of concrete were divided into three categories of crumb rubber content: 0%, 5% and 10%.
(c) The type of studs was Grade 4.6, with ultimate tensile strength of 400 MPa and yield strength of 240 MPa. Three diameters, 16 mm (M16), 19 mm (M19) and 22 mm (M22) were used and the heights of the stud were 90 mm, 110 mm and 130 mm, respectively.
(d) The diameter of reinforced bar was 10 mm, and its yield strength was 335 MPa.

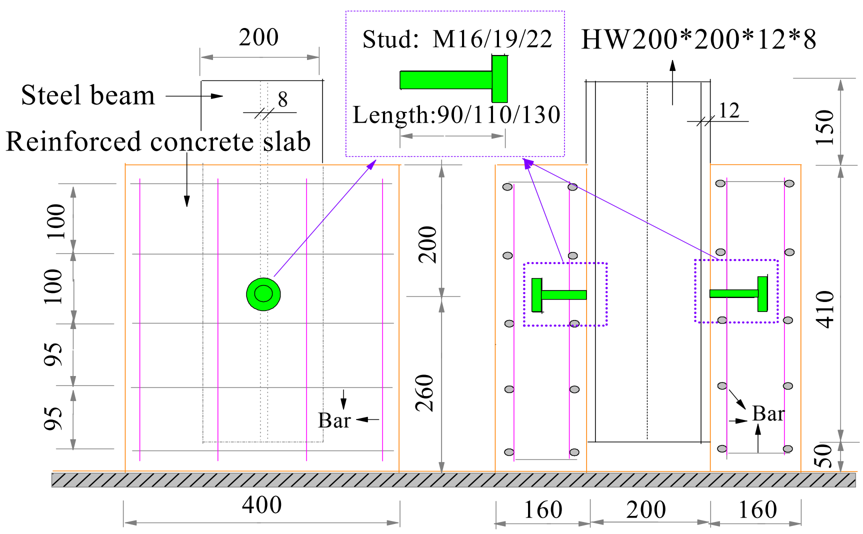



Fig. 1 Size of push-out test specimen: front view (left); side view (right)

### *3.2 Test set-up*

The push-out specimens were tested in a hydraulic servo testing machine with a capacity of 1000 kN, shown in Fig. 2. The loading speed can be controlled efficiently and the loading can be stopped while reaching the pre-defined load values or fatigue cycles.

In the test, the fatigue load frequency was 5 Hz and the data were collected when the fatigue cycles reaches the cycles of 0, 10,000, 30,000, 50,000, 80,000, 100,000, 150,000, 200,000, 300,000. Hence, after reaching the specified cycles, dynamic parameters were tested first, such as dynamic slips and displacements, at the same time the fatigue load frequency changed into 1 Hz. After that the static data were collected during the static loading process. The static loading gradually went back to 0 then to the median load during 5 minutes. Then the fatigue loading continued and the frequency was 5 Hz. If the slip or the displacement increased obviously, the sampling time-interval can be shorten. When the displacement increased rapidly and heard the fracture cracking sound, the loading should be stopped.

The static-dynamic strain indicator, with the maximum frequency of 200 Hz, was used and the displacement was measured by 1/1000 mm electronic displacement meter, called HY-100 and HY-50. Longitudinal slip between concrete slab and steel beam and the lift-up values of the concrete slab were measured in the tests. Fig. 2(b) shows the arrangement of electronic displacement meter on one side. Strain of studs on the upper and lower surfaces at a 1/2 and 1/5 distances to the roots of studs were measured.


(a) Front view (b) Side view (c) Loading device

Fig. 2 Test set-up

Table 3 Concrete mix composition

| Group | Rubber content | Recycled tyre rubber (kg) | Cement (kg) | Stone (kg) | Sand (kg) | Water (kg) | Water reducing (kg) |
|---|---|---|---|---|---|---|---|
| Concrete | 0% | 0 | 295 | 1087 | 839 | 165 | 2.174 |
| RRFC-1 | 5% | 50 | 400 | 703 | 1004 | 169 | 2.391 |
| RRFC-2 | 10% | 100 | 590 | 1230 | 412 | 168 | 6.522 |

Table 4 Mean value of material properties of concrete

| Rubber content | Compressive strength (kN) | Elastic modulus (GPa) | Peak strain | Ultimate strain |
|---|---|---|---|---|
| 0% | 43.30 | 33.72 | 0.002725 | 0.003516 |
| 5% | 36.27 | 27.90 | 0.002996 | 0.004223 |
| 10% | 43.70 | 21.83 | 0.004323 | 0.006943 |

### *3.3 Material properties of RRFC*

The material properties of the new employed component recycled tyre rubber-filled concrete were investigated first before the fatigue tests. The raw materials used for test samples were fine aggregate, coarse aggregate, water and recycled tyre rubber within 1~2 mm diameters. Besides, the high range water-reducing admixture was adopted to insure the high fluidity of concrete mixing. The mix proportions of recycled tyre rubber followed the principle of volume percentage method and the rubber content was divided into three groups 0% (normal concrete), 5% (50 kg/m$^3$) and 10% (100 kg/m$^3$). The mixed proportions are shown in Table 3. The mean value of test results in material properties tests, including compressive strength tests, elastic modulus tests and compressive stress-strain full curve tests are shown in Table 4.

## 4. Static behavior of studs

The bearing capacities of shear studs were investigated before the fatigue tests. The test results are listed below (Han *et al*. 2015a, b). The material and standard of static push-out test specimen are the same as fatigue ones, shown in Table 2 and the static and fatigue test specimens were casted at the same time. Furthermore, the ultimate strength of shear studs obtained from static tests was compared with those calculated by design codes of Eurocode-4, AASHTO LRFD and GB50017-2003.

The static push-out tests of shear studs were conducted and the average ultimate loads were calculated by three specimens in each group, shown in Table 5. All the static specimens showed typical shank failure and the damage was ductile. In the subsequent fatigue test, the load amplitude were designed not exceed the 50% of ultimate load per stud.

Table 5 Static push-out test results

| Specimens | Concrete strength grade | Rubber content | Size of Studs | Average ultimate load (kN) | Average ultimate slip (mm) |
|---|---|---|---|---|---|
| PS-1~3 | C30 | 0% | M16 | 79.7 | 6.1 |
| PS-4~6 | | 5% | | 78.5 | 7.8 |
| PS-7~9 | | 10% | | 75.0 | 9.1 |
| PS-10~12 | | 0% | M19 | 90.1 | 6.6 |
| PS-13~15 | | 10% | | 90.8 | 10.2 |
| PS-16~18 | | 0% | M22 | 139.0 | 7.5 |
| PS-19~21 | | 10% | | 142.3 | 11.9 |

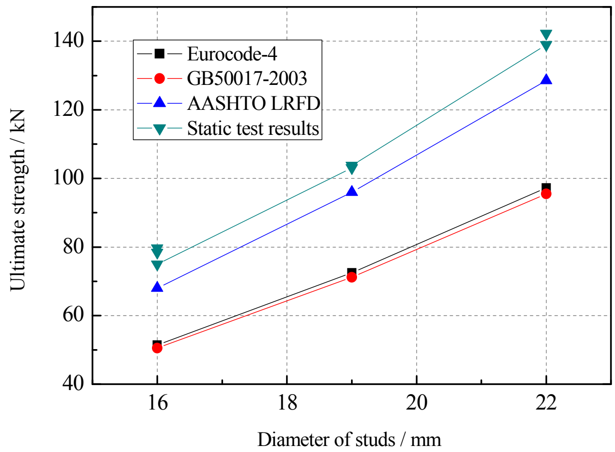



Fig. 3 Comparison between design codes and test results

Fig. 3 shows the comparison between static test results and three national codes, including Eurocode-4, AASHTO LRFD and GB50017-2003. It has been proved that the calculation results followed current codes have certain assurances for the shear studs in RRFC from comparison with test results according to Fig. 3. Thus, the current codes are still valid and we can use these codes to calculate the shear studs in RRFC. All the push-out test results were higher than the design shear strength in three national codes and the design shear strength in AASHTO LRFD was closer to the test results, while the Eurocode-4 and GB50017-2003 gave relatively conservative values.

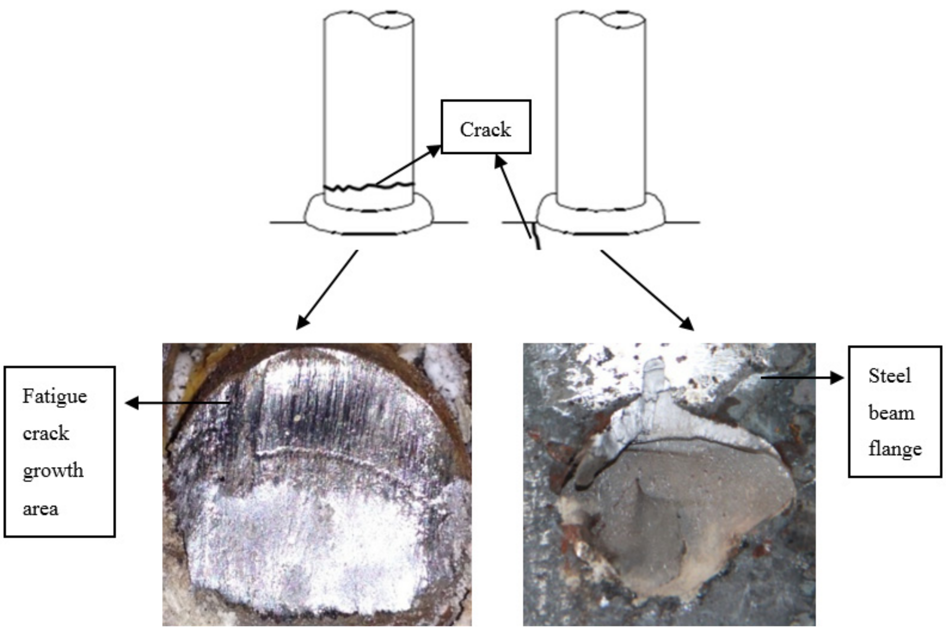



Fig. 4 Fatigue failure modes of fatigue push-out tests: Fatigue failure of stud (Left); Tearing off the base metal (right)

Table 6 Results of fatigue push-out tests

| Specimens | Rubber content | Size of studs | Load amplitude /kN | Median load /kN | Stress amplitude /MPa | Median stress /MPa | Fatigue life $/10^4$ |
|---|---|---|---|---|---|---|---|
| PF-1 | 0% | M16 | 60 | 50 | 149.28 | 124.40 | 6.90 |
| PF-4 | 5% | | | | | | 13.48 |
| PF-7 | 10% | | | | | | 1.2 (welding defect) |
| PF-2 | 0% | | 52 | 50 | 129.38 | | 78.22 |
| PF-5 | 5% | | | | | | 101.79 |
| PF-8 | 10% | | | | | | 129.57 |
| PF-3 | 0% | | 40 | 37 | 99.52 | 92.06 | 0.35 (welding defect) |
| PF-6 | 5% | | | | | | 300 (unbroken) |
| PF-9 | 10% | | | | | | 300 (unbroken) |
| PF-10 | 0% | M19 | 85 | 61 | 187.34 | 107.63 | 6.61 |
| PF-11 | 0% | | 54 | 61 | 95.28 | | 68.00 |
| PF-13 | 10% | | | | | | 87.58 |
| PF-12 | 0% | | 43 | 61 | 75.87 | | 300 (unbroken) |
| PF-14 | 0% | M22 | 100 | 61 | 131.60 | 80.28 | 2.5 |
| PF-15 | 0% | | 76 | 61 | 100.02 | | 74.58 |
| PF-16 | 10% | | | | | | 231.00 |

## 5. Fatigue test results and discussion

### *5.1 Modes of failure*

Based on the test results of the 16 fatigue push-out tests, the failure modes can be categorized by fatigue failure of shear stud and tearing off the base metal, shown in Fig. 4. In the former failure mode, the stud had plastic deformation and the damage was ductile. The failure surface of stud shown in Fig. 4 can be divided into fatigue crack growth area and static shearing area. That means when the rest of the stud’s cross section can’t bear the peak fatigue loading, the fatigue failure will happen. The latter failure mode was brittle and mostly happened in larger diameter of shear studs. Hence, the ratio between the diameter of studs and the thickness of the base metal (steel beam flange) should be controlled and the value should be between 1.33 and 1.58. Because in the fatigue tests, all the studs with 16 mm diameter happened the former failure mode, while the studs with 19 mm and 22 mm diameters sometimes happened the former failure mode, sometimes happened the latter one. Thus, the ratio range is calculated between studs with 16 mm and 19 mm diameters. The test results are summarized in Table 6. Besides, according to the lift-up value between concrete slab and steel beam, upper and lower lift-ups were both happened in the current tests.

Table 6 shows that the fatigue lives of studs tend to fall precipitously in response to the growing stress amplitude. In PF-6, PF-9 and PF-12, fatigue failure did not occur in the first three million fatigue cycles, while the designed two million times in GB50017-2003 was reached. In addition, after tests, we found that PF-3 and PF-7 in the current tests contained welding defects,

(a) PF-3

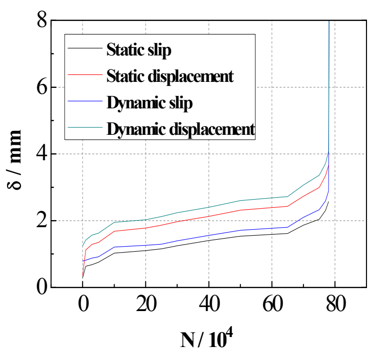
(b) PF-7

Fig. 5 Welding defects in PF-3 and PF-7

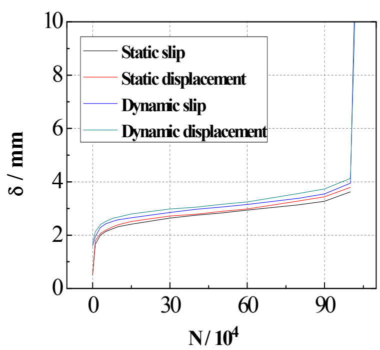
shown in Fig. 5. From Fig. 5, we can see that there were lots of welding porosities at the weld zone, which didn't fall under normal damage conditions and should be ignored when drawing the conclusion. Welding defects cutting down the fatigue lives tremendously. Hence, avoiding the welding defect is of great importance in real project.

### *5.2 Residual slip, displacement and fatigue lives*

The static slip, static displacement, dynamic slip and dynamic displacement were all measured after a certain number of cycles in the current tests. Fig. 6 takes two specimens as examples and results show that the trends for the four curves are basically the same. At the beginning, the curves had a remarkable growth, and then the growth turned to be steady. Finally the curves suddenly grew without bound, meaning the fatigue failure occurred. Moreover, the residual slip values under dynamic loading were a little bigger than static ones and these happed to be the same of the displacement values. This is because the static values were measured from 0 kN to median loads (median load is the average of peak load and valley load), while the dynamic ones was measured from valley load to peak load (peak load minus valley load is the amplitude). Hence, the following paper was discussed with the more accurate dynamic values.

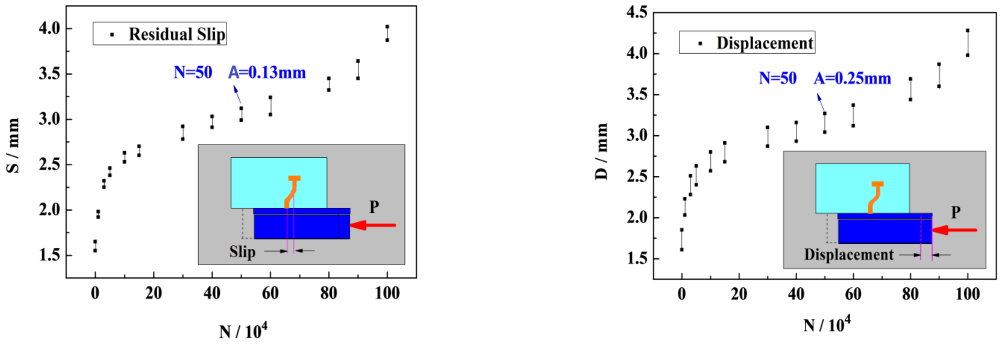



(a) PF-2 (0%)




(b) PF-5 (5%)

Fig. 6 Residual slip, displacement and fatigue lives




(a) Residual slip-N (b) Displacement-N

Fig. 7 Dynamic residual slips and displacements in PF-5 (A means Amplitude)

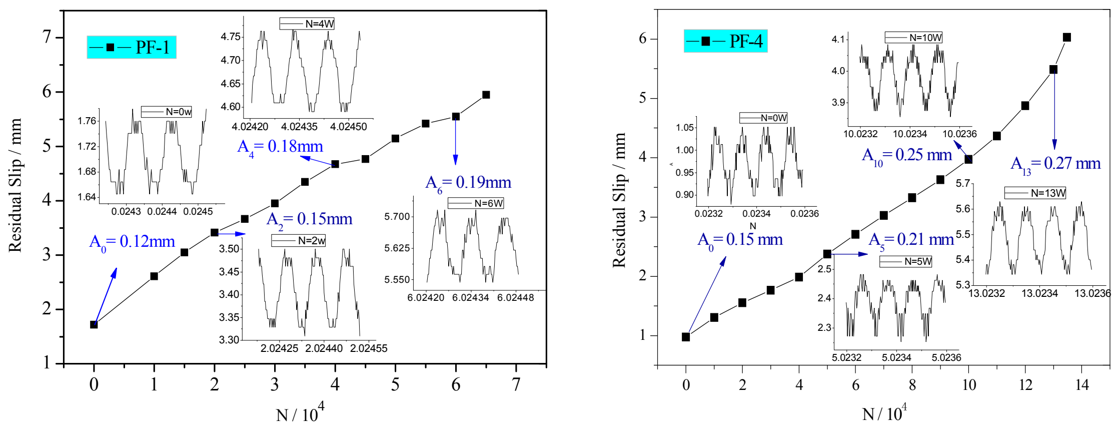
Fig. 7 shows the residual slips and displacements under dynamic loads of PF-5. The amplitudes of slips increased with the growing *N*, while the amplitudes of the displacement seemed to have no obvious change. Furthermore, the amplitudes of displacements were obviously larger than those of slips. Since a part of displacement was digested by the up-lift (separation) between steel beam and concrete slab. Hence, in order to investigate the fatigue behavior of studs, the residual slip values was more accurate than displacement ones.

### *5.3 Discussion*

(1) 1 The effect of the recycled tyre rubber contents

Five groups were compared below to investigate the effects of the recycled tyre rubber contents on the fatigue lives, ultimate residual slips value and amplitudes of studs. The diameter of studs, the dynamic loading system and the loading values in each group were the same, and the only different was the rubber content.

(a) PF-1 & PF-4




(a) PF-1 (b) PF-4

Fig. 8 Residual slip-N curves of PF-1 and PF-4

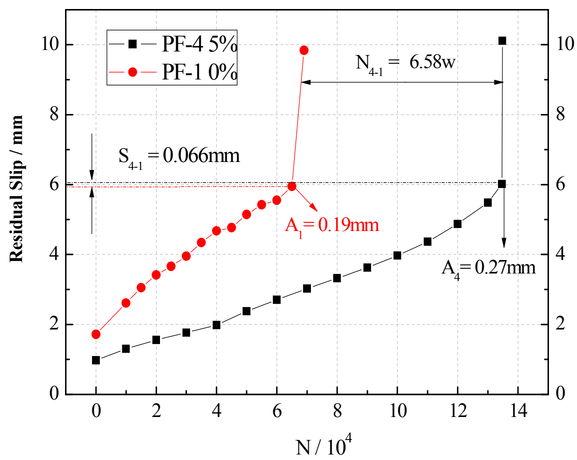



Fig. 9 Residual slip-N curves of PF-1 and PF-4

Fig. 8 describes the increments of residual slips during the loading processes of PF-1 and PF-4, respectively. At the same time, four stages of dynamic slips were enlarged in each group. We can see from Fig. 8 that the amplitudes of slips were increased with the increasing *N*, and the increasing range of PF-4 was larger than that of PF-1. Fig. 9 placed the two groups together and we can see that the fatigue life and amplitude of ultimate residual slip of PF-4 were all lager than those of PF-1. Hence, PF-4 has the better ductility. Also, the rigidity degeneration in this group went very fast and PF-1 went significantly faster than PF-4. In this group the fatigue lives were short due to the large stress amplitude. The fatigue life of studs in PF-4 in RRFC was nearly twice as large as PF-1 in normal concrete.

(b) PF-2, PF-5 & PF-8

From Fig. 10, we can also draw the conclusion that the more rubber contents in the surrounding concrete, the larger fatigue lives and residual slips of shear studs. The reason is that the elasticity

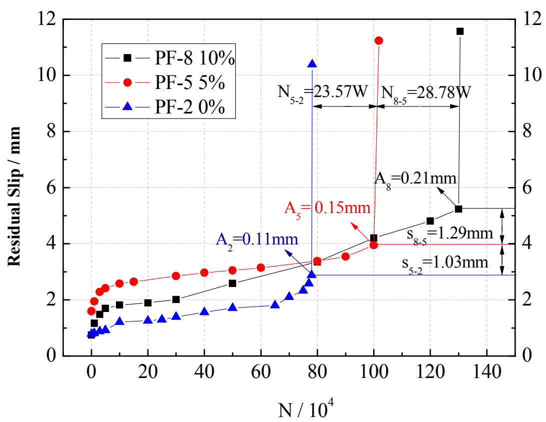



Fig. 10 Residual slip-N curves of PF-2, PF-5 and PF-8

modulus of RRFC is smaller than normal concrete, so under the same stress its deformation can be larger. More importantly, this group systematically shows the influence of three different rubber contents on the fatigue life of studs. The results show that the fatigue life of studs in PF-8(10%) was 1.66 and 1.27 times of those in PF-2(0%) and PF-5(5%), respectively.

(c) PF-6 & PF-9 (unbroken)

Although PF-6 and PF-9 did not happen fatigue failure due to the small stress amplitude, the residual slip of PF-9 was found obviously larger than PF-6 in Fig. 11. Hence, the former with 10% recycled tyre rubber content has better ductility.

(d) PF-11, PF-13 (M19) & PF-15, PF-16 (M22)

Fig. 12 shows the residual slips and the fatigue lives of lager diameters of studs. Fig. 12(a)) shows the studs with 19 mm diameter and Fig. 12(b) shows the studs with 22 mm. It happened to

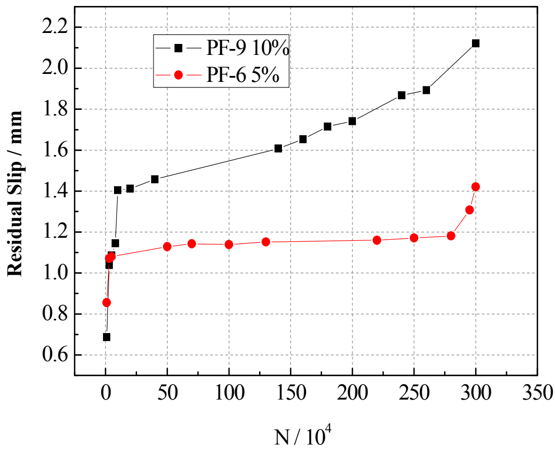
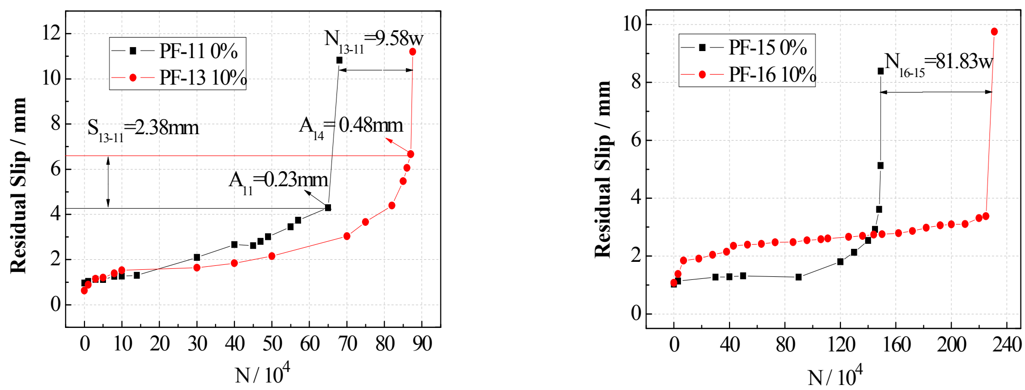



Fig. 11 Residual slip-N curves of PF-6 and PF-9




(a) PF-11 & PF-13 (M19) (b) PF-16 & PF-17 (M22)

Fig. 12 Residual slip-N curves of M19 and M22 be the same in the lager diameters of studs, so the aforementioned conclusion can also be proved. We can see from test results that fatigue lives of studs with the same diameter in 10% RRFC are 1.29 time and 3.10 times of those in normal concrete.

Normal concrete (without rubber content) is a kind of brittle material. While recycled tyre rubber in RRFC can be regarded as tiny plastic units in concrete and rubber can absorb energy effectively due to its strong deformability, thus it changes the concrete into plastic performance. Especially under cyclic loads, according to Hernadez-Olivares *et al.* (2007), the elasticity modulus of RRFC can be strengthened and RRFC has lower damage speed compared with normal concrete. In addition, rubber can also disturb the propagation and breakthrough of cracks in RRFC.

Due to above reasons, studs have more compatible deformation in ductile RRFC. When bearing the fatigue loadings, RRFC can provide more sufficient and longer supporting to shear studs and transfer the force effectively. Moreover, from the failure mode and the value of strain gauge, we can analysis that the head of studs was firmly embedded in concrete and the plastic strain firstly appeared on the root of studs. Hence, if the plastic deformation, namely the interface slip of stud's root is too large, the studs will be pulled to damage (Han *et al*. 2015a, b). According to the test data, the average ultimate slip value is equal to a quarter of studs' diameter.

(2) The effect of stress amplitude

As mentioned before, the stress amplitude was inversely proportional to the fatigue lives of studs. Two specimens, PF-4 and PF-5, under the different stress amplitudes were shown in Fig. 13. We can see that under larger stress amplitude, the growth of PF-4 was almost liner, while PF-5 had a rapid growth at the beginning and then went slowly. Hence, under larger stress amplitude, specimen has liner degradation and the fatigue failure happens quickly.

(3) Stiffness degradation of push-out specimens

Fig. 14 shows the stiffness degradations of three specimens under the same stress amplitude. All the three specimens had a drop of stiffness at the first beginning, and then the stiffness of the stud in normal concrete tend to be stable, while the stiffness of PF-5 and PF-8 in RRFC has a slow rebound. The stiffness of studs in PF-8 is more lager than that of PF-5. Hence, the stiffness of studs under fatigue loads increases with more rubber content in surrounding concrete.

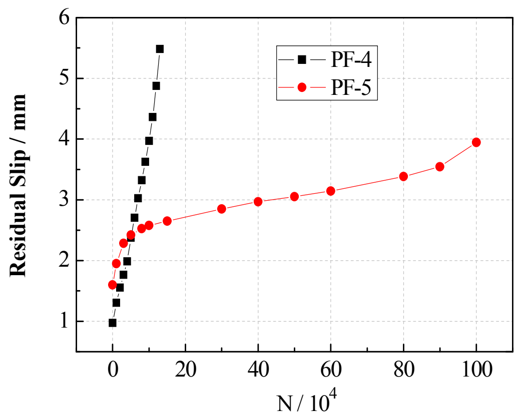



Fig. 13 Residual slip-N curves of PF-4 and PF-5

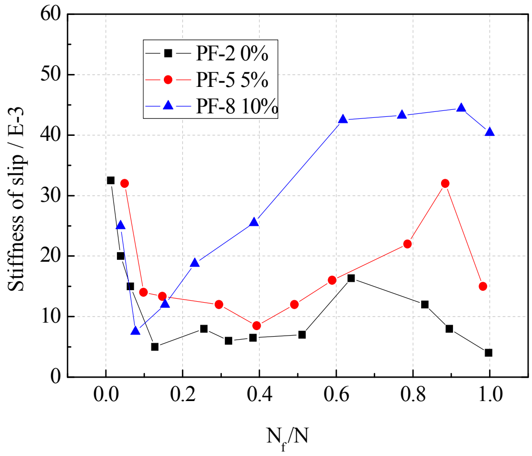



Fig. 14 Stiffness of residual slip

(4) Comparison between test results and other researches

A comparison between test results and other researches is presented in Fig. 15. According to Fig. 15, there is a liner relationship between horizontal and vertical axis. The results show that under the same stress amplitude, the smaller fatigue life of N (the value of vertical axis), the safer results for the researches, meaning the high reliability. From Fig. 15 we can see that Slutter and Fisher's results are the safest and Nie's result is safer when the stress amplitude is small. Among three national codes, the Eurocode 4, the Japanese Standard and the AASHTO LRFD, the Eurocode 4 and the AASHTO LRFD are safer than the Japanese Standard because the black line and the green line are below the red one. When the stress amplitude is large, the AASHTO LRFD

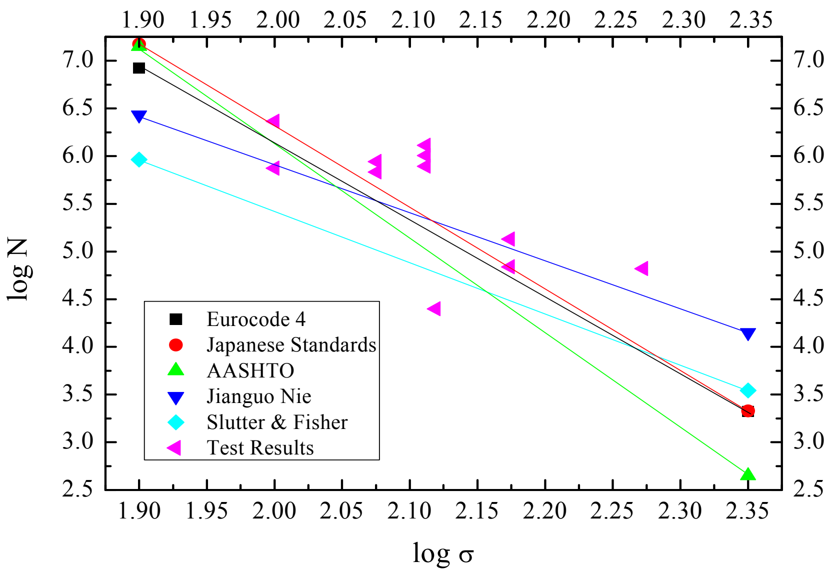



Fig. 15 Comparison between test results and other research

is safer than the Eurocode 4 since the green line is lower than the black one. We can also draw this conclusion from our test results, when the stress amplitude is 149.28 MPa, the limit N value of the Eurocode 4, the Japanese Standard, the AASHTO LRFD, Nie's and Slutter and Fisher are 53800, 68000, 25700, 112800 and 30900, while the test results is 69000. This means Nie's results is not safe enough for design and the test result is nearly the same as the Japanese Standard's result. Thus, the Japanese Standard is the least conservative one and the AASHTO LRFD is the safest. At the same time, the purple dots represent the test results in this paper and most of the test points were distributed above the AASHTO LRFD. Thus, the AASHTO LRFD highlights of its safety.

We can also draw conclusion from Fig. 14 that the fatigue lives of large studs are slightly shorter than smaller ones, because the further ones above the lines are almost M16, while on or below the lines are almost M19 and M22. This is because welding of large diameter of studs is relatively difficult due to size effect.

## 6. Conclusions

Recycled tyre rubber-filled concrete was firstly employed into steel-concrete composite beams to investigate its effect on the fatigue behavior of shear studs. 16 standard fatigue push-out tests of steel and RRFC composite beam were conducted in the current paper. Different recycled tyre rubber contents of RRFC, stress amplitude and diameters of stud were taken into consideration. Following conclusions have been drawn:

- The failure modes of push-out tests can be defined into fatigue failure of shear stud and tearing off the base metal. In the former failure mode, the stud has plastic deformation and the damage is ductile. Moreover, the failure surface of stud can be divided into fatigue crack growth area and static shearing area. While the latter failure mode is brittle and undesirable.
- A part of displacement value was digested by the up-lift value between steel beam and concrete slab. Hence, the residual slip value is more accurate to investigate the fatigue behavior of studs. According to our tests, the average ultimate slip value is nearly equal to a quarter of studs' diameter.
- The average fatigue lives of studs in 5% and 10% RRFC are 1.6 and 2.0 times greater of those in normal concrete, respectively. Furthermore, both the stiffness and ductility of studs increase with the more rubber content in the surrounding concrete.
- Stress amplitude is inversely proportional to the fatigue life of studs. Under larger stress amplitude, the test specimens have liner degradation and the fatigue failure happens quickly.
- The fatigue life of large studs is slightly shorter than the smaller ones and using larger ones has the risk of tearing off the base metal. Hence, using large diameter stud should be considered carefully in practical engineering and the ratio of the diameter of studs and the thickness of the base metal (steel beam flange) should be limited.
- It has been proved that the current codes are still valid for the RRFC and large studs. Most of the test points were distributed above the AASHTO LRFD. When the stress amplitude is large, the AASHTO LRFD highlights of its safety and Eurocode 4 is safer than the Japanese Standard.

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